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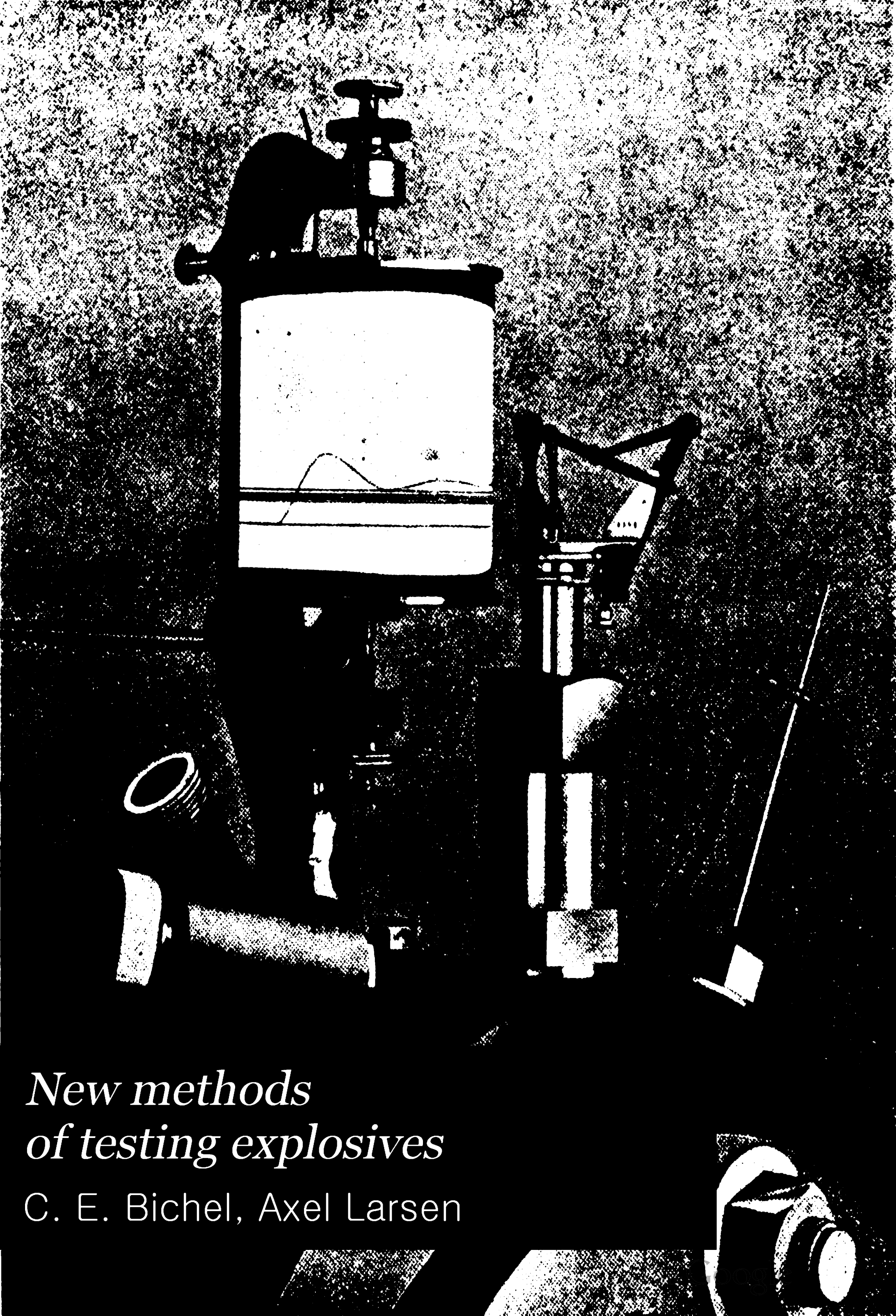

New methods of testing explosives

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NEW METHODS OF TESTING EXPLOSIVES

INTRODUCTORY

> **"In every department of serious inquiry men are glad to find the same conclusions reached by different methods—the more different the better. Of course, it is obvious that if one started from absolutely certain premises or data, and could exclude all fallacies in the process of making logical inferences from them, then the conclusions would need no support. Certain data and certain logic must yield certain conclusions. Not in one in ten thousand of his inquiries can the man of science command these desirable conditions; and so he ever seeks to reach by more methods than one that which, he hopes, is a valid conclusion."—*Scientific Notes*, PALL MALL GAZETTE.**

UNTIL about fifteen years ago black powder and dynamite were almost the only explosives used in practical mining. The danger entailed by their use in workings where gas was met with, had, however, been generally recognised, and the admitted expediency of abolishing their employment in "fiery" mines or seams presently brought about a material change of affairs.

To-day, the use of gunpowder has almost entirely ceased in collieries troubled with gas, and even in quarries it has been largely abandoned. Dynamite has perhaps stood its ground rather better, but this material, too, has had to yield wherever pit-gas or dangerous quantities of coal-dust abounded, both in fact being almost universally superseded nowadays by so-called "safety" explosives.

As long as there were only two kinds of explosives, their selection appears to have involved but scant embarrassment. Thus, for getting soft coal or for obtaining large blocks in rock-blasting, gunpowder was the material chosen. If, on the other hand, the coal was too hard or the cost of boring too high to permit the use of powder, the stronger explosive, dynamite, was resorted to. But since the risk of shot-firing in fiery or dusty mines was fully recognised an entirely new factor became a desideratum, that, namely, of rendering the operation safe.

The higher demands thus made on the inventive skill of manufacturers resulted in the closer study of the essential properties of explosives and the phenomena of their decomposition, and the name of Mr. C. E. Bichel (inventor of "Carbonite" and Managing Director of the Carbonite Explosives Company Limited, Hamburg) stands prominent amongst the pioneers in this movement. By his recent achievements in practical research and his initiative in devising entirely new methods and apparatus for throwing light on the causes of ignition of firedamp by explosives, he has added to our technical knowledge of these substances a chapter of extreme interest and incontestable value.

In the present account of Mr. Bichel's investigations, published for the first time in England, the writer has adhered throughout to the original serial reports save such re-editing of the material as was found expedient in order to furnish a complete presentment.

Due credit is given by Mr. Bichel to Drs. Mettegang, Schmidt, and Rudeloff (superintendent chemists at his works) for their services in connection with the researches hereinafter described, a special tribute being paid to Dr. Mettegang to whom the task of designing the apparatus and of conducting the experimental work was particularly entrusted.

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HISTORICAL

At the Carbonite Works at Schlebusch the following questions were made the subject of practical research:

1. *Why does a smaller quantity of one explosive than of another cause ignition of firedamp?*
2. *What are the incidental phenomena and the influences tending to promote such result?*

and

3. *In what manner do they co-operate in producing it?*

In order to solve these problems several types of special apparatus were devised and built and a series of experiments, extending over the last eight years, carried out. At the outset it was decided to forego the more purely theoretical treatment of the subject which had been inaugurated by earlier (French) investigators, in regard to the question of safety in presence of firedamp, and to follow almost exclusively the experimental method. In treating the matter theoretically one is obliged to make certain assumptions and to apply laws the correctness of which, under abnormal pressures and temperatures, has not been universally accepted. Apart from this, the theoretical method did not commend itself, for the reason that the manufacturers' object was to apply the practical knowledge experimentally gained, to the production of new and manifestly better explosive compounds.

Their method of achieving this was to carry out experiments with heavy charges, varying the composition of the explosive, and to record the difference in effect thus produced. A description of the methods and the apparatus used for the purposes and also for gauging the effects of the various explosives manufactured by the Carbonite Explosives Company as a result of their experiments, will be found in the following pages. It has been deemed convenient, for purposes of comparison, to add gunpowder to the list of explosives on account of its peculiar mode of action in the presence of gas.

In order that the definite object of these trials may be clearly appreciated, a few remarks bearing upon the question of explosives *versus* firedamp, though confined mainly to the conditions prevailing in England and Germany, may here be introduced.

Through the researches of the various Firedamp Commissions and Miners' Associations it has been conclusively proved that all known explosives, provided they are used in sufficiently large quantities, ignite and explode both pit-gas and coal-dust. It is solely in regard to *the limit of the dangerous quantity* that they differ from one another. This difference is, however, so considerable that, for example, whilst 5 grammes of black powder, blasting gelatine, gelatine dynamite, or No. 1 dynamite are sufficient to fire a given mixture of firedamp and coal-dust, the explosion, for example, of 1000 grammes of carbonite fails to ignite it. It is therefore essential to ascertain what maximum quantity of explosive can safely be used without causing an ignition. In his paper read at the Fifth International Congress of Applied Chemistry in Berlin in the year 1903, Watteyne very appropriately termed this critical quantity of explosive the *charge-limite*, a definition which might well be universally adopted.

In Germany it is now the rule to fire unstemmed shots from a cylindrical steel-block, or "gun", into a gaseous atmosphere holding coal-dust in suspension; the flame, or flash, of the explosion is thus discharged right into the inflammable mixture and cannot fail to come into intimate contact with it. In England, on the contrary, the shots are carefully stemmed; consequently, there can only be actual contact in the case of explosives which either emit a flash of such reach or of such duration that it will outlast the dislodgment of the stemming (such as gunpowder, or explosives of similar slow combustion) or which detonate so rapidly that the stemming is violently expelled and the inflammable mixture is fired by the "flash," *i.e.*, by the gases of decomposition before they have had time to cool below the ignition temperature. The latter is what occurs in the case of blasting gelatine and analogous compounds.

Seeing that the methods of experiment in the two countries differ so entirely in principle, it can hardly be wondered at if the conclusions drawn are correspondingly at issue. In Germany a standard safety-limit of at least 300 to 350 grammes (about 10½ to 12 ounces) per single shot is considered indispensable in view of the working conditions existing there, and but few of the explosives hall-marked in England as specially permitted would come up to the German standard. In England it is furthermore required that mining explosives should detonate completely.* But it should be borne in mind that the incomplete decomposition of ammonium

---

*** This requirement is only exacted when the explosive is undergoing the test at Woolwich, and I understand that the reason for requiring that ammonium nitrate explosives should detonate completely is that it is desirable that they should be tested under the conditions of maximum tendency to ignite the gas mixture, a condition which is not fulfilled when they detonate partially.—Tr.**

nitrate compounds by no means renders these explosives less safe—indeed the contrary is the general case, whilst on the other hand nitro-glycerine compounds usually burn away with a strong flame when incompletely detonated and thus undoubtedly become, for the time being, a source of considerable danger underground. In Germany but little importance is attached to the matter of complete detonation, probably owing to the fact that nowadays nearly all shots are fired by specially appointed shot-firers who are required to see that proper stemming is used.

Again, the diameter of the Government trial gallery, or tunnel, at Woolwich is very small, a restriction which is further accentuated by the fact that a 16-per-cent. mixture of ordinary lighting gas is used therein, whilst in Germany a 7-per-cent. to 9-per-cent. mixture of methane gas and air is considered sufficient. On the other hand the standard charge used for the Woolwich tests does not exceed the equivalent of 4 ozs. of Kieselguhr dynamite. The English test is thus less severe as regards quantity and stemming, but more severe than the German standard in other respects.*

For twenty years such experiments have been continually carried out in Germany, and the number of testing-stations owned by private factories and authorities has been steadily growing. This movement has had a stimulating effect on the industry of explosives, and both the number of, and demand for, safety explosives are continually increasing. New explosives were thus introduced and their composition adjusted with a view to satisfying the conditions of the tests mentioned.

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* See Report of H.M. Inspector of Explosives on Visits to Continental Factories and Testing-Stations (1905); also their Annual Report for 1904 (p. 140).—Tr.

Several contain nitro-glycerine (Carbonite and similar compounds); others have ammonium nitrate as base (Roburite, Dahmenite, Westphalite, Kœln-Rottweil safety powder, Progressite, &c.), whilst a third type contains nitrate of ammonia with the addition of a small percentage of nitro-glycerine (Ammoncarbonit, Donarit). The advantages of the nitro-glycerine types are high charging density, assured detonation, and the fact of their being moisture-proof. The nitrate of ammonia type is eminently suitable for a safety explosive on account of the large amount of water formed on firing, but it possesses the disadvantages of hygroscopic tendency and irregular detonation. The object of the additions of small quantities of nitro-glycerine to the nitrate in the third type is to effect a compromise between the advantages and disadvantages of the two former types, although, certainly, much may be done during manufacture towards mitigating the drawbacks of the nitrate of ammonia type.

As regards safety explosives the regulations in Germany demand that the composition shall be printed on, or placed inside, the cardboard boxes. In this way inspection is greatly facilitated.

Quite a controversy has arisen as to whether nitro-glycerine or nitrate of ammonia is the best base for safety explosives; the dispute may possibly issue in a combination of both.

Nitro-glycerine, being a liquid of high density, is a most suitable ingredient inasmuch as it produces a plastic explosive which can be thoroughly pressed into the bore-holes and is therefore likely to produce the maximum effect.

Ammonium nitrate explosives are so little susceptible to fire, shock, or percussion, that the German railways agree to carry them as ordinary goods; but their comparative lightness renders them less effective than the nitro-glycerine compounds. Hence their utility is confined to workings where the ground is soft and the cost of drilling moderate. In hard rock it is impossible to get suitable charges of these explosives into the boreholes. A certain length of the latter must be left for stemming, and the centre of energy of the charge would thus be too near the mouth of the hole. There are, therefore, many cases in which nitrate of ammonia explosives would be useless, whilst nitro-glycerine compounds would answer perfectly well.

So far an addition of 30 per cent. of nitro-glycerine has proved the permissible maximum for safety explosives, higher proportions being detrimental to this quality. Indeed, the safety of these explosives is inversely proportionate to their strength; if the latter is increased, the former is proportionately reduced, and *vice versa.* By experimenting with given raw materials the most favourable combination for attaining the highest strength may be determined. The appended tabulated results serve as a guide in estimating what may be achieved in this direction, and thus to assist in the further development of the explosives industry.

The products of detonation of an explosive consist of solids, liquids and gaseous bodies. The reaction involves development of heat which, in the case of the gases, produces a pressure which reaches its maximum more or less quickly according to the rate of detonation. The kinetic energy imparted to these products by the detonation acts as an impact on the surrounding walls. When the borehole is shattered, causing an increase of the space originally occupied by the explosive, the gases, although already in the act of cooling down, are still capable of exerting a certain pressure on the enclosing walls. In the presence of firedamp the risk of ignition depends both upon the time required for developing the maximum temperature, and on the surface area of the explosive gases at the moment when such maximum is attained. When an explosive is fired from a mortar, the gases of detonation form a cone the axis of which represents the length of the flame.

All phenomena attending the detonation of explosive substances are, of course, determined by their chemical composition. The latter will be found in the first columns of Table I. in which the more important phenomena and characteristics are recorded. Much importance naturally attaches to the mode of manufacture, *i.e.*, to the intimate mixing of the ingredients, the purity of raw materials, the mechanical treatment, cartridge-making, packing, &c., factors which all producers strive to bring to the highest degree of perfection; but though exerting a marked influence on the final result, they are incapable of measurement and cannot, therefore, be computed numerically. The condition and specific gravity of an explosive (*i.e.*, the highest obtainable charging density, or the ratio between weight in grammes and volume in cubic centimetres) are likewise features of great importance.

Factors which enter more directly into the question of safety and power of an explosive will be found in Table I., columns 4 to 10; these refer to the nature and amount of gaseous products, the heat developed, the maximum pressure, the rate of detonation, the lead-block expansion, and the length and duration of the flame produced.

The actual pressures and volumes of gases developed on explosion were determined by means of Bichel's pressure-gauge (Engl. Pat. No. 18,273^{98}), a calorimeter being used in ascertaining the heat-values and a specially constructed photographic apparatus to record the flame. The rate of detonation was measured by Boulengé's and Mettegang's chronographs. All tests were made with charges of over 100 grammes and a No. 8 detonator, and incomplete detonations were particularly guarded against. All shots were fired electrically.

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CHAPTER I

TESTING-STATIONS

ALTHOUGH testing-stations have been common in Germany for a long time past, strange to say, there are not two of them which produce identical results. Nevertheless, the results of trials made at each individual testing-station are fairly uniform amongst themselves, and the differences between the various explosives when compared with one another are also, in general, concordant.

It has frequently been suggested, and was again proposed at the International Congress, to establish some uniformity both in the system and in the mode of conducting these experiments. These proposals have hitherto failed, however, owing to the fact that the parties interested could not agree to adopt a standard mixture of artificial gas. Such an artificial mixture was objected to, and certainly not without justification, by those who had natural pit-gas emanations at their disposal, and were thus enabled to make direct comparisons of explosives under conditions actually existing underground—an advantage readily understood. But even gas-"blowers" are frequently of very varying composition, and their general adoption as standards for experimental purposes would therefore entail a prohibitive amount of supervision and checking. The dimensions of the testing-galleries and the material selected for construction likewise lack general uniformity. When building new testing-stations, or repairing existing ones, it is desirable that these should resemble in close detail some other existing station, preferably, perhaps, that belonging to the Gelsenkirchen Coal Mining Corporation.

Moreover, endeavours to secure a greater uniformity in the explosive gas-and-air mixture are advisable, such as by preparing artificial equivalents of natural pit-gas. A degree of inflammability could thus be attained on stations using an artificial mixture, similar to that possessed by natural gas. Discrepancies between the results obtained at two stations working with natural pit-gas of different composition would, doubtless, still exist, but sufficient uniformity could even here be attained if such stations would agree to adapt the gas-percentage to standardised conditions of inflammability.

Factors, however, exist, peculiar to each testing-station, which assert themselves differently on different days. The incongruities resulting therefrom have caused much trouble to investigators. There is no clue to their origin, and the behaviour under given circumstances of one and the same testing-gallery is at times quite erratic, even capricious. The cause probably lies in concurrent local influences not easily determined or removed, such as atmospheric pressure, humidity, wind velocity, varying friction of the explosive gas-mixture against the inner walls of the gallery, long exposure to the sun's heat, and other partially known and varying circumstances.

The joint action of several of these influences may occasionally cause the same explosive to give very dissimilar results under conditions otherwise analogous. Many unsuccessful attempts have been made to trace the source of these differences, and it is only after long experience and observation at any given station that such influences to a certain extent may be calibrated and allowed for; they will never quite disappear. It is therefore inadvisable to depend on the results obtained during a single day, but judgment should be based upon observations made at different dates. However, the so-called bad days of a testing-station, that is, the days on which the concurrence of unfavourable circumstances is manifestly interfering with the working, are not the rule, but the exception. On such occasions experiments should be abandoned, and resumed only when well-known explosives again give standard results.

CHAPTER II

POWER-GAUGES

All known contrivances for measuring the pressure of or the work done by explosives are subject to the disadvantage that they permit of accurate comparison only between explosives possessing similar characteristics. It is, however, of great importance to both manufacturers and consumers to know how dissimilar explosives (particularly those having different rates of detonation) compare with each other in regard to their respective pressures in a borehole, *i.e.*, to their power to do work, in order to form any estimate of their practical value.

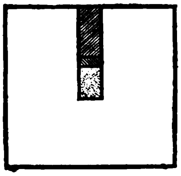
THE TRAUZL LEAD-BLOCK TEST

The simplest of these apparatus and, at the same time, the most easy to handle, is the Trauzl lead-block.

In this test a charge of 10 grammes of explosive with detonator is loaded into a central cavity, 12 cm. deep and 2 cm. wide, in a cylindrical lead-block 20 cm. high by 20 cm. in diameter. Loose sand with moist clay on top is used as stemming, the block being firmly fixed by means of wedges and a wrought-iron clamp. The charge is fired by electricity. When the charge is exploded, a pear-shaped expansion of the bore is formed. The expansion is measured by filling it with water from a graduated glass beaker. Figs. 1 and 2 show sections of a Trauzl lead-block before and after the shot.

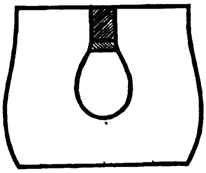
Provided that the blocks are from one cast and of the same temperature when used, the Trauzl test, if carefully carried out and applied to analogous types of explosives, may be considered as fairly reliable, but a direct comparison of *different* explosives is not possible by this test, as it gives unfavourable and misleading results for explosives of slow detonation. Very quick explosives throw out the stemming completely, while slower ones loosen it. The wedges are either loosened or they drop off entirely. Explosives of very slow detonation (or rather "combustion"), such as gunpowder, do not effect any appreciable expansion at all, as the gases escape through the stemming long before reaching their maximum pressure and temperature. The higher the velocity of detonation, the greater the visible effect in the block.

FIG. 1



BEFORE SHOT

FIG. 2



AFTER SHOT

The appended lead-block readings are introduced in order to furnish some sort of direct record of comparative strengths, and to give a general idea of the results obtainable by this method under the latest standard conditions. They were taken under the new rules and conditions laid down by the Fifth International Congress of Applied Chemistry, without, however, deducting the volume of the borehole (about 60 cub. centimetres).

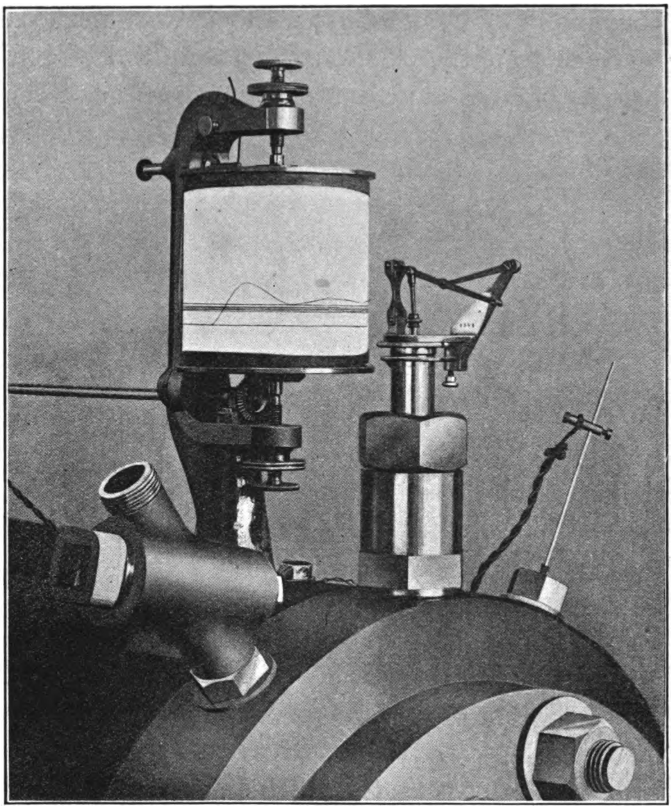
BICHEL'S PRESSURE-GAUGE

In order to measure the pressure developed by explosives detonating at different rates of velocity it is essential to provide an apparatus in which an escape of the generated gases is rendered impossible.

It is with this chief consideration in view that the new pressure-gauge has been designed.

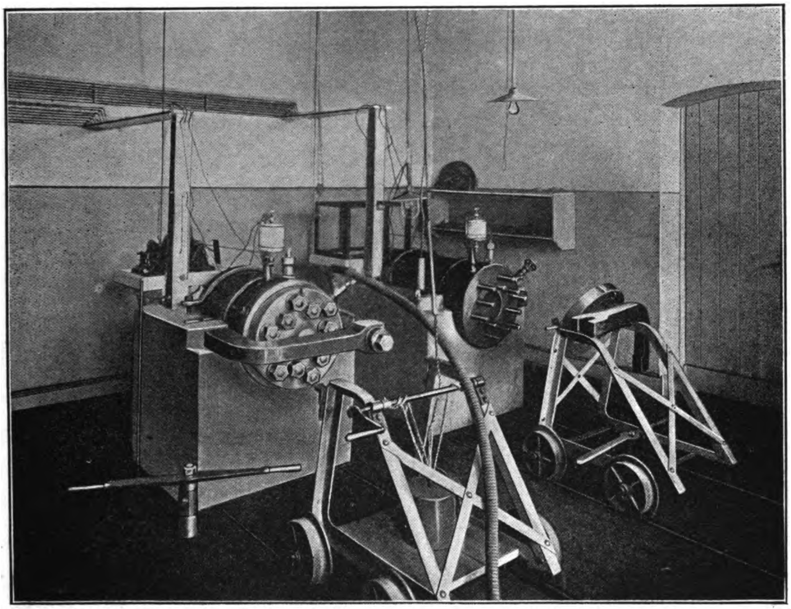
This apparatus consists of a steel cylinder 80 centimetres (31½ inches) long and 50 cm. (19¾ inches) in diameter, resting on a masonry foundation and kept in position by two anchored clamps. The explosive chamber is 20 cm. (7⅞ in.) in diameter and 48 cm. (19 in.) deep, so that its capacity is 15 litres. A second cylinder has a capacity of 20 litres. The charge to be tested is placed

FIG. 3



in the chamber on a small wirework tripod and fitted with an electric detonator fuse, the wires of which are carried through the walls of the cylinder. The explosive chamber is closed by means of a strong steel cover, which is held in position by stout screw bolts and clamp. Lead washers ensure a perfectly gas-tight closure. By means of an aperture pierced through the wall of the cylinder connected with an air-pump, the air in the chamber may be exhausted down to 20 mm. mercury column. Vertically above the test-charge is an adjustable valve attachment comprising an indicator with piston of the kind used for steam-engines. A pencil or style is adapted diagrammatically to mark a rotary drum set in motion by clockwork (Fig. 3). The speed of rotation is measured for each shot by the number of signals which record the revolutions. Fig. 4 is an illustration of the apparatus,

FIG. 4



open and shut. In the case of explosives of slow detonation, the indicator draws a shallow curve; with rapidly detonating explosives a steeper ascending curve is marked, which, on the gases cooling down, gradually becomes a horizontal line, and, as such, records the pressure exerted by the cooled gases inside the chamber. From this curve the products of explosion—solids, fluids, and gases, —may be deduced. The gases may also be withdrawn through the aperture for analysis.

The report of the shot is scarcely audible. Charges of 1500 grammes of gunpowder and 300 grammes of high* explosives have been fired without damaging the steel cylinder or any of its separate parts. About thirty minutes are required to prepare and fire each shot. Several thousands of shots have been fired with the two apparatus erected at the Schlebusch works.

The diagrams are read in the same manner as those of a steam-engine indicator. The initial deflection, owing to the momentum of the indicator and connecting parts, extends somewhat beyond the point of true maximum pressure. The pressure and rate of detonation developed by the explosive are in direct proportion to such excess. With some practice, therefore, the true maximum pressure may be located at a point easily found in the upper curvature.

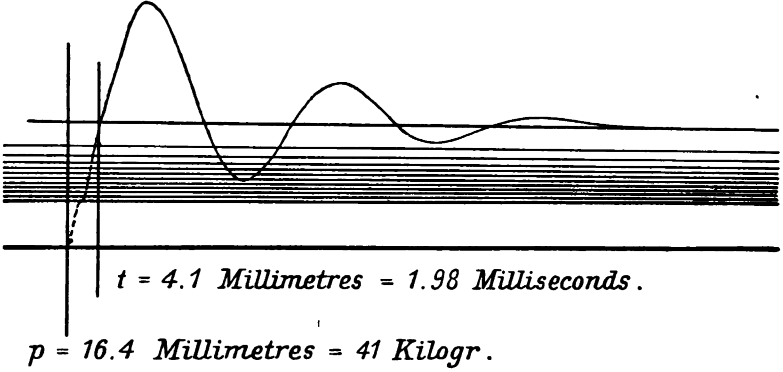
The indicated pressures rarely deviate more than 2 or 3 per cent. from the actual. Some diagrams are shown in Figs. 5, 6, and 7.

The diagram (curve) is no ultimate criterion of the rate of detonation, but it furnishes an illustration of the more or less rapid development of the pressure. Owing to the inertia of its connecting parts the indicator is incapable of registering absolute values of the former. The true rate of detonation has therefore been determined by direct measurement as hereinafter described. Nevertheless, the curve offers a sufficient guide for forming an opinion upon any hitherto unknown explosive and for properly classifying it by results amongst existing and familiar compounds.

---

* *Detonating.*—In this translation the word "brisant" (explosives) has sometimes been used in preference to the rather inadequate expression "high." As the latter is limited, in its technical sense, to the adjective form, and is incapable of inflection, the substitution would seem justified. To students of foreign literature on explosives it will scarcely even appear as a neologism.—Tr.

FIG. 5

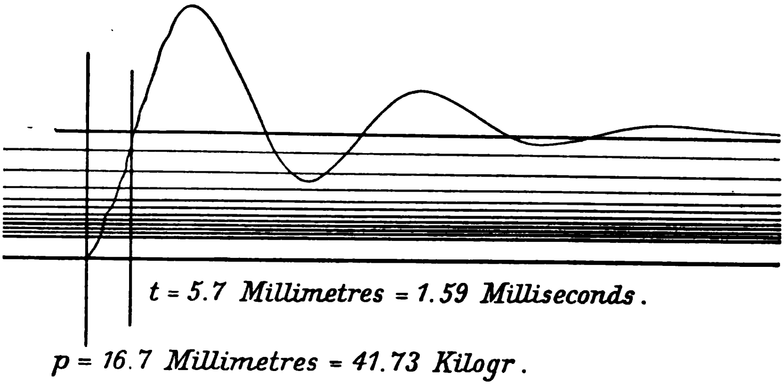


PRESSURE-CURVES

100 grammes Gelatine Dynamite
Detonator No. 8 (2 grammes)
Capacity of chamber = 15 litres
Inner surface of chamber = 3600 square centimetres
Rotary speed of drum = 3.42 metres per second
Tension of spring: 0.4 millimetre = 1 kilogramme per square centimetre
Bar: 757 millimetres
Vacuum = 27 millimetres
Viscosity of lubricating oil at 15° C. = 63

The indicated pressures of explosives detonated in the explosive chamber are undoubtedly lowered owing to the heat absorbed during the development of such pressure, by the surrounding walls of the cylinder. The more slowly such pressure is developed, and the greater tendency there is for certain gases of explosion to condense, the greater will the difference be between the indicated pressure and that which would have resulted had no such influence existed. In order to compare these two values, it is necessary to calculate the cooling capacity of the inner surfaces. This may be done by increasing the superficial area of the surroundings whilst keeping the volume constant; thus, with the assistance of both apparatus, three different areas (*e.g.*, 3600, 6600 and 7600 sq. cm.) may be obtained in combination with one and the same chamber capacity (15 litres). The pressure maxima obtained under these conditions lie along an almost straight line, the inclination of which also indicates the rate of cooling and condensa-

FIG. 6

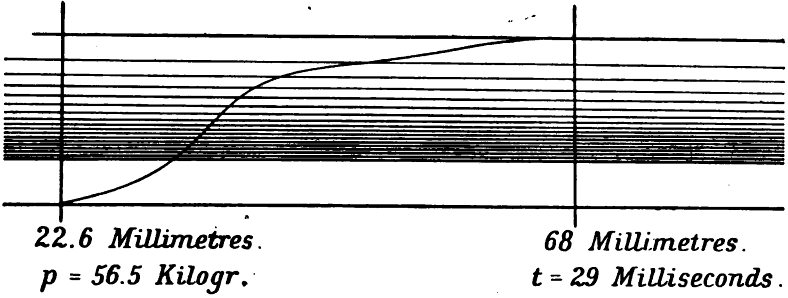


PRESSURE-CURVES

100 grammes Gelatine Dynamite
Detonator No. 8 (2 grammes)
Capacity of chamber = 15 litres
Inner surface of chamber = 3600 square centimetres
Rotary speed of drum = 3.58 metres per second
Tension of spring: 0.4 millimetre = 1 kilogramme per square centimetre
Bar: 757 millimetres
Vacuum = 27 millimetres
Viscosity of lubricating oil at 15° C. = 63

tion of the explosive gases. Thus it will be found that the pressure-readings obtained with ammonium nitrate explosives for different areas follow a much steeper line than those yielded by nitro-glycerine compounds. As shown in Table II., a third part to half a part of the weight of the former is converted into steam which rapidly condenses. This fact should be borne in mind when estimating the efficiency of these explosives, the more so as the ammonium nitrate compounds do not detonate as quickly as those consisting of nitro-glycerine and a dope. As different ground is constantly encountered in practical mining, it follows that the loss of efficiency sustained through condensation is likewise a variable quantity.

FIG. 7



PRESSURE-CURVES

300 grammes Gunpowder
Detonator No. 8 (2 grammes)
Capacity of chamber = 15 litres
Inner surface of chamber = 3600 square centimetres
Rotary speed of drum = 2.335 metres per second
Tension of spring = 1 kilogramme per square centimetre
Barometer: 753 millimetres
Vacuum = 20 millimetres
Viscosity of lubricating oil at 15° C. = 63

A series of shots is fired with each of the above-mentioned areas, the average pressures obtained being marked down as ordinates, and the surface areas as abscissæ. On connecting the terminals of the ordinates an almost straight line is obtained which, if continued until it cuts the axis of ordinates (surface abscissa = "o") will mark the actual pressure after elimination of surface influence. The pressure readings given in Table I. have all been found in this way.

The following example may further elucidate this:

Fifty grammes of Kieselguhr dynamite, on being exploded in the 15-litre chamber at various superficial areas, gave the following pressures:

Internal Surface Area	Pressure
7600 square centimetres	17.4 kilogrammes per square centimetre
6600 ,, ,,	18.5 ,, ,, ,,
5000 ,, ,,	19.7 ,, ,, ,,
3600 ,, ,,	20.76 ,, ,, ,,

On treating these values in the manner described, the pressure at a surface area = "o" is found to be 24.0 kilo. (see Fig. 8). The same charge gave the following pressures when exploded under identical conditions in a chamber of half the above capacity:

Internal Surface Area	Pressure
6000 square centimetres	37.7 kilogrammes per square centimetre
5000 ,, ,,	39.8 ,, ,, ,,
3720 ,, ,,	41.6 ,, ,, ,,
3360 ,, ,,	41.9 ,, ,, ,,
2100 ,, ,,	44.75 ,, ,, ,,

Proceeding as before, a pressure of 48.2 kilo. at a superficial area = "o" is arrived at (Fig. 8). At these charging densities the pressures prove to be inversely proportional to the volumes, thus confirming Boyle's law.

This elimination of the surface-influence has, besides, an additional object. The apparatus permits only the use of low charging densities. If a charge of, say, 100 grammes of an explosive with a density of 1 is fired in a chamber having a capacity of 15 litres, then the charging density is only $\frac{100}{15000}$, or $\frac{1}{150}$, while in a usual borehole it would theoretically be $\frac{1}{1}$. By reducing the chambers and employing stronger springs, a density of $\frac{1}{25}$ may be reached without risk of injury to the cylinder. But even this density is very low. By setting down as ordinates the direct readings of pressure at densities varying between $\frac{1}{150}$ and $\frac{1}{25}$, without taking the surface influence into account, and as abscissæ the corresponding sizes of the chamber, a hyperbolic curve is obtained, the equation of which may be found experimentally. But if, on the other hand, the pressures at the same densities are set down after due elimination of surface-influence, then the connecting line will be found to be straight. It may therefore be taken for granted (pending future evidence to the contrary, perhaps through the introduction of stronger apparatus and higher densities) that the pressure obtained with a density of $\frac{1}{150}$ and corrected for surface-influence is directly proportional to those obtained with higher densities. It would be well if this proposition were made the subject of wider research, as it promises to lead to a more intimate, and, in many

FIG. 8

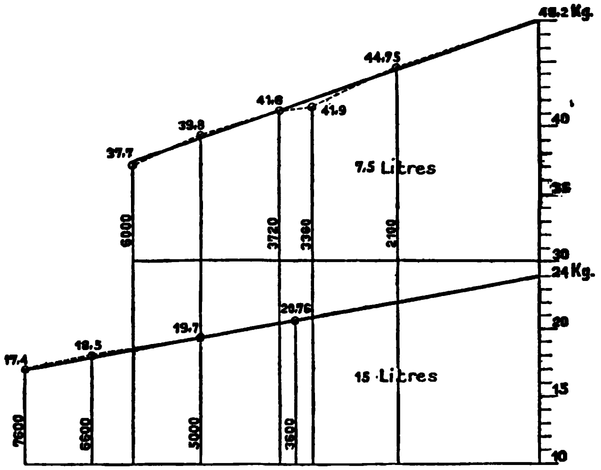


DIAGRAM SHOWING PRESSURES OF 50 GRAM. KIESELGUHR-DYNAMITE IN 7½ AND 15 LITRE CHAMBERS AT DIFFERENT INTERNAL SURFACE-AREAS other respects valuable, knowledge of the behaviour of gases under high pressures and temperatures.

Applying the pressure corresponding to a density of $\frac{1}{150}$ to the most favourable densities obtained by experiment, assuming the above proposition to be accurate, we arrive at the following values for the explosives under consideration :

	Highest density of charging	Pressure in own volume kg. per sq. cm.*	Relative Pressure
Gunpowder . .	1.04	2917	1.0
Blasting Gelatine .	1.63	17,213	5.9
Kieselguhr Dynamite	1.58	11,420	4.0
Gelatine Dynamite .	1.67	13,878	4.7
Donarite . . .	1.31	9570	3.3
Ammoncarbonit I. .	1.11	7792	2.7
Ammoncarbonit .	1.19	7541	2.6
Thunderite . .	1.07	6099	2.1
Carbonit II. . .	1.49	7755	2.7
Carbonit I. . .	1.55	7533	2.6
Kohlencarbonit . .	1.42	6603	2.3
Carbonite . . .	1.08	4309	1.5

The absolute as well as the comparative values given in this Table agree fairly with practical experience and are not inconsistent with thermo-chemical results.

If the lead-block expansions caused by explosives be compared with the respective pressure-readings shown in Table I. and in the accompanying Plate (Fig. 17) it will be seen that while the expansions and pressure-readings for explosives of rapid detonation agree almost exactly, the pressure-readings in the case of slower explosives are higher than those obtained by the lead expansion method. This confirms what has already been said, that the lead-block gives reliable results with explosives which detonate instantaneously, while the steel cylinder registers the maximum pressure of all the gases generated.

---

* 1 kilogr. per sq. cm. = 14.223 lbs. per sq. inch.

It will be noticed that the ammonium nitrate explosives, especially in cases of small charges, were irregular and lacked facility of detonation. At times they failed to detonate with completeness, and slow decomposition with generation of red vapours was of frequent occurrence. It was only in charges of 300 grammes and upwards that they could be properly and uniformly detonated in the steel cylinder.

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CHAPTER III

PRODUCTS OF COMBUSTION

DURING explosion the moment at which the maximum heat is reached and maximum pressure developed is of particular importance, seeing that on these two factors depend both the efficiency of the explosive and the greatest danger of gas-ignition. This moment cannot, however, be exactly determined; nor can the chemical and physical condition of its resulting products be ascertained. After the explosion the chemical and physical analysis of the cooled products is an easy matter; but they are now by no means the same as they were at the moment of explosion, at which all solids probably liquefy or gasify. On cooling in the chamber, such products may be partially liquefied or even become solid. As these fumes in practice are disseminated through the surrounding air, their composition is no doubt of importance from a hygienic point of view. But so far as efficiency and safety in blasting are concerned, it is only necessary to investigate the ultimate solids, liquids and gases produced at the moment of detonation.

In obtaining the readings contained in Table II., it was found expedient to insert a strong stop-valve between chamber and indicator in order to prevent the full force of the explosion from acting directly on the somewhat larger indicating piston and the weaker spring used for these tests.

After the fumes have cooled to the temperature of the room this valve is opened, and the pressure registered by the indicator is then taken. The product of volume and pressure gives the quantity of gases generated, their weight in litres being deduced from their specific gravity as ascertained by a Lux hydrostatic balance. On opening the chamber, the solid and liquid residues found therein are collected and weighed. The weight of all the products, solid, liquid and gaseous, must, of course, represent the entire weight of the charge exploded.

From data obtained in this manner regarding the composition of the cooled products of explosion (Table II.), the nature of the latter at the actual moment of detonation was deduced, it being assumed that the water had then existed as vapour, the alkaline salts as melted carbonates, and the carbon dioxide as gas.

The determination of the fumes of Blasting Gelatine, Carbonite, and Donarit may serve as an example. The figures given in the Table represent the average result of several experiments.

1. BLASTING GELATINE:

100 grammes fired with No. 8 detonator (containing 2 grammes of fulminate) in a 15-litre chamber at 16.56° C. —Bar. 760 mm. (29.92 inches). The indicated pressure after cooling for $\frac{3}{4}$ hour was = 2.15 kilo.; or = 2.222 atmospheres. On adding 1 atmosphere to compensate for the partial vacuum in the chamber, the indicated pressure is = 3.222 atmospheres or 3.205 atmospheres at 15°C. At normal atmospheric pressure and at a temperature of 15°C. the gases would thus occupy a space of 48.075 litres.

Upon a Lux balance, one litre weighs 1.510 grammes; 48.075 litres therefore weigh 72.5 grammes, which, when deducted from 102 grammes (weight of the charge), leaves 29.5 grammes as still remaining in the chamber and, necessarily, in the form of water. 29.5 grammes of water at 15°C. and 760 mm. Bar. = 38.7 litres of steam. Hence 100 grammes of Blasting Gelatine yield:

72.5 grammes gaseous products,
29.5 grammes water.

2. CARBONITE:

206 grammes of Carbonite fired in its wrappers with detonator No. 8 in the 15-litre chamber at 16.81°C. Bar. = 750 mm. Indicated pressure = 7.13 kilo. per sq. cm. = 6.9 atmospheres, which, allowing for the 28½ inches vacuum in the chamber, gives 8.21 atmospheres at 15°C. and 760 mm. Bar. Hence 125.15 litres cooled gases weigh 118.8 grammes. Residue left in chamber = 87.2 grammes, of which 1.6082 grammes were raised to red-heat in the combustion-furnace, yielding:

0.2411 gramme water
0.3313 gramme carbon dioxide
1.0372 grammes ash.

Hence, 87.2 grammes contain:

13.13 grammes water = 17.20 litres, gaseous
17.95 grammes carbon-dioxide = 9.63 litres gaseous CO_2
52.2 grammes residue, supposed to have been melted alkaline carbonate at the actual moment of explosion.

3. DONARIT:

206 grammes, fired in its wrapper with No. 8 detonator in the 15-litre chamber at 17.65°C. Bar. 748 mm. Indicated pressure 7.28 kilo. Add allowance for 28½ inches vacuum = 1 atmosphere, which gives 8.296 atmospheres at 15°C. and 760 mm. Bar.

Hence 124.44 litres of cooled gases weighing 134.6 grammes; 67.95 grammes of water were removed from the chamber, partly by decantation and partly by calcium-chloride apparatus. 67.95 grammes of water = 89.10 litres steam at 15°C. and 760 mm. Bar. As 71.4 grammes were theoretically to be accounted for, there was a shortage of 3.45 grammes.

On detonation, the gaseous products attain their highest temperature, and produce the corresponding maximum pressure. The solids, probably in a molten state, participate in the expansion only so far as the space they occupy, and are, therefore, incapable of increasing the pressure. If a charge is properly stemmed, the conversion of the explosive into gases is completed within the space occupied by the charge. The higher the density of charging, the less the corresponding gas-space, and consequently the greater the gas pressure or energy of the explosive.

1	2 Gaseous products by detonation of 1 kilo.	3 Charging volume of 1 kilo.	4 Gas per litre charging volume	5 Calories developed per kilo.
	Litres	Litres	Litres	
Gunpowder	386	.961	401	574
Blasting Gelatine	851	.614	1386	1422
Kieselguhr Dynamite	536	.633	847	1170
Gelatine Dynamite	487	.599	813	1321
Donarit	1023	.763	1341	836
Ammoncarbonit I.	922	.900	1024	850
Ammoncarbonit	930	.840	1107	757
Thunderite	1021	.935	1092	777
Carbonit II.	746	.671	1112	602
Carbonit I.	773	.645	1198	601
Kohlencarbonit.	816	.704	1160	506
Carbonite.	729	.926	783	576

Column 4 shows the ratio between the volumes occupied by a given quantity of explosive before and after detonation, no residual solids being taken into account

The volume, as well as the specific gravity of the gases generated by different explosives, vary considerably, but the ultimate pressure will always depend both upon the quantity of gaseous products generated within the space occupied by the charge, and on the number of calories or heat-units developed. The Table on p. 29 demonstrates this.

The initial pressure, *i.e.*, that which is developed in the charging-volume by virtue of the initial heat-energy of the combined products of detonation—cannot be accurately measured by existing apparatus and methods, but the *rate* at which such pressure is fully developed may be gauged by the rapidity of detonation which, as will be shown later, is determinable.

CHAPTER IV

HEAT OF DECOMPOSITION

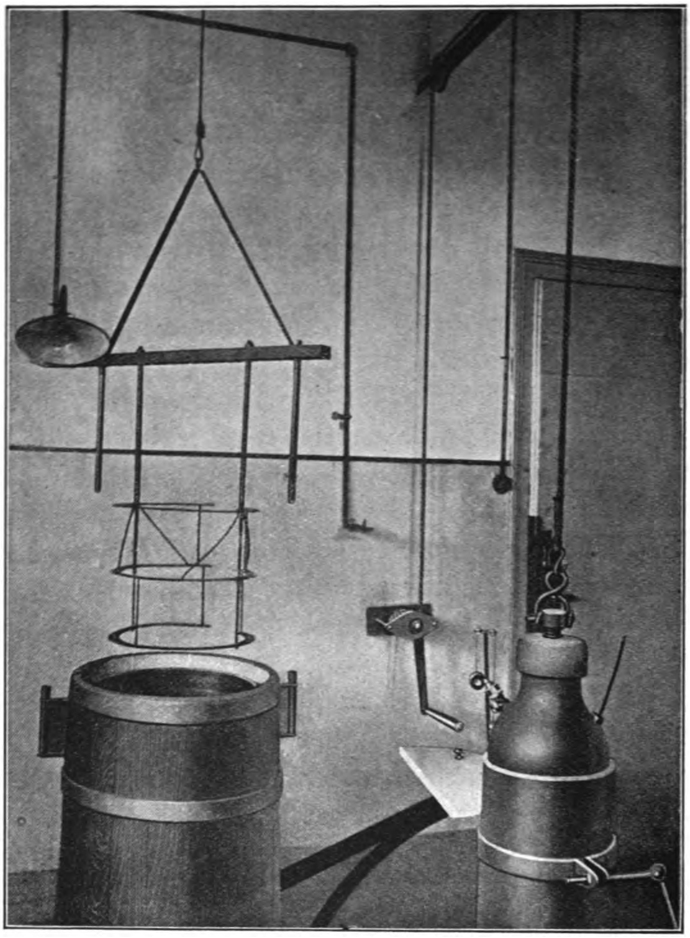
APART from the ordinary difficulties in measuring very high temperatures, an explosion takes place in such an infinitely brief space of time as to preclude ordinary means of observation. With the aid of Berthelot's calorimeter it is, however, possible to ascertain what quantity of heat is emitted on detonation of a given charge, provided that this apparatus is of the size requisite for detonations of 100 grammes of explosive or more.

Under the directions of Dr. Mettegang an apparatus was constructed for this purpose, consisting of a wrought-steel bottle-shaped bomb with a capacity of 30 litres; it was provided with an exhaust valve, and could be hermetically closed. The explosive was suspended in the centre of the bomb and fired by electricity; with the exception of such modifications as were necessarily required for higher pressures and larger quantities, the calorimetric arrangements otherwise remained the same as usual.

The amount of test water used was about 70 litres. Total heat-absorbing capacity, including shell and sundry metallic parts, 71,719 (small) calories. The stirring was mechanical.

Fig. 9 is an illustration of the apparatus. As in the case of determining the products of decomposition, it was found necessary to apply the moment of observation to the moment of detonation, so as to eliminate ulterior reactions. As such may be mentioned:

FIG. 9



CALORIMETER

FIRSTLY.—The heat *absorbed* through inside condensation of aqueous vapour contained in the fumes; and

SECONDLY.—The formation heat *liberated* by the carbonates combining with CO_2 to form bicarbonates.

The following example, showing how the heat generated by Ammoncarbonit I. is found, may further elucidate the method:

The detonation of 70 grammes of this explosive raised the temperature of the test-water 1.05°C. (corrected for temperature of room). Hence the total heat disengaged $=71,719 \times 1.05 = 75,305$ calories. After deducting 1381 calories for the detonator, there remain 73,924 calories, or, for one kilogramme of explosive, 1056 (large) calories.

According to the Table of observed decomposition products one kilogramme of Ammoncarbonit I. forms 341.3 grammes of water. This water (gaseous) would be condensed, thereby disengaging 202 calories, which must also be deducted, leaving 854 calories.

One kilogramme of Ammoncarbonit I. contains 90 grammes of potassium and sodium nitrates. The conversion into|bicarbonates of the carbonate formed by 1 kilogramme of these nitrates, involves a formation-heat of 35.8 calories. Hence for 90 grammes $=3.2$ calories. After finally deducting these, there still remain 850.8 calories net as representing the actual heat-energy of 1 kilogramme Ammoncarbonit I.

The calorimetric readings were applied to determining the temperature of explosion on purely experimental lines coupled with the data obtained by analysing the cooled gases of detonation.

In calculating the temperature of explosion the well-known formula:—

$$t = \frac{Q}{c}$$

was followed, where

t = temperature

Q = heat disengaged by the decomposition, per kilogramme of explosive expressed in calories (observed with Mettegang's adapted calorimeter), and

c = specific heat of the decomposition products (as determined by analysis of the contents of Bichel's Pressure-gauge)

The values of specific heat were taken from Mallard and Le Chatelier's calculations according to the formula $c = a + bt$, a and b being constants.

Hence the equation:

$$t = \frac{Q}{a + bt}; \text{ or, } at + bt_2 = Q$$

from which t is found.

Of the temperatures calculated, the lowest is that of Kohlencarbonit, viz., 1561°C, the highest being that of Blasting Gelatine, viz., 3216°C. The ratio between these limit-values is therefore = 1 : 2.

CHAPTER V

RATE OF DETONATION

ALL explosives require some initial impulse in order to explode. This impulse must be sufficiently strong to ensure perfect detonation. Once started, the explosion is propagated more or less quickly according to incidental conditions, both chemical and physical. The greater the rate at which an explosive is decomposed on detonation, the greater is the ballistic energy with which the gases press upon the walls of the shot-hole. That the knowledge of the rate of detonation is an essential requisite for judging the efficiency of an explosive is too self-evident to require any special proof; that the same is equally important as regards safety in gas, however, is shown in Table I.

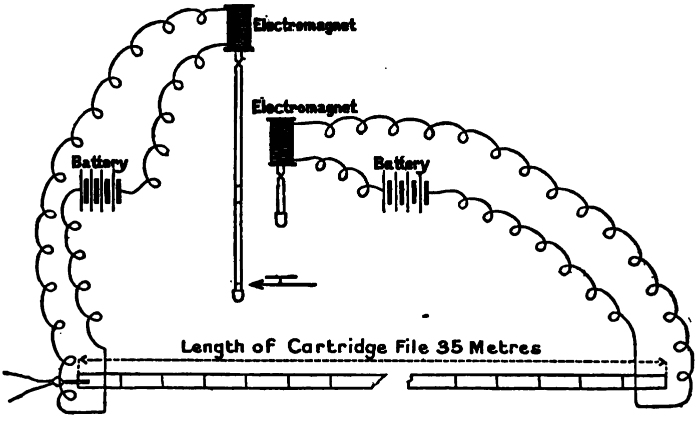
In order to determine the rate of detonation a suitable number of cartridges of the same diameter were originally placed end to end on the ground, forming, as it were, one single cartridge, care being taken to press the cartridges well into contact with each other. This was, indeed, actually carried out in the case of the plastic explosives, one long "cord" of explosive being drawn from the cartridge-machine. The file or cord generally measured 35 metres in length, which proved sufficient to obtain accurate records.

It soon became evident, however, that the rate of detonation depends to a certain extent upon the diameter of the cartridges, and that it increases with the latter. Cartridges of an explosive of a high rate of detonation may therefore for purposes of this test require smaller diameters than those of material detonating less rapidly. Dynamite shows no appreciable increase of rapidity beyond a cartridge-diameter of 30 millimetres, while, in the case of ammonium nitrate explosives, such an increase is still very marked in diameters up to 50 millimetres. The tabulated velocities all refer to diameters of 30 millimeters (1¼ inches); this being the dimension most frequently met with in practice.

As these experiments involved the firing of somewhat formidable quantities of explosives, it was found necessary to carry them out at a locality well removed from habitations, &c. The first tests were made conjointly with the Testing Commission of the Royal Artillery and were continued by the United Dynamite Factories at the Wahn Dynamite Works.

The rate of detonation from end to end of the long file of cartridges was at first registered by means of 3 or 4 Le Boulengé's electro-ballistic chronographs, such as are commonly used for measuring the velocity of projectiles. The two electric circuits passing through the two ends of the cartridge-file were thus consecutively interrupted by the explosion (Fig. 10). The different velocities were then calculated in the usual manner from the difference between the drop-readings of two magnetically suspended bars, obtained by the consecutive interruption of the two circuits. In the course of investigation, however, some doubt arose as to the conclusiveness of the results thus obtained. Some of the conditions under which the method operated were doubtful, whilst others were distinctly unfavourable. Apart from the inconvenience attending the firing of such large quantities of high explosives, the heavy charges made the experiments somewhat costly. Likewise, the results needed correction for the time required for demagnetising the electro-magnets, for fall of the drop-bars, and for the action of certain of the mechanical parts; these, however, might be determined as constants. Again, as regards the measuring of the time elapsing between the breaking of the circuits at the two ends of the cartridge-file, although decomposition had progressed far enough to rupture the circuit it was impossible to ascertain whether such was complete or only partial at the moment the wires were broken. It was only proved that the detonation-wave was initiated and propagated throughout the whole length of cartridges, and that the "detonation-time" (the interval between the two distinct breaks of the circuits) varied with each kind of explosive.

FIG. 10



METTEGANG'S RECORDER

An improved method for determining the rate of detonation was explained in detail at the Fifth Congress of Applied Chemistry in Berlin by Dr. Mettegang of Schlebusch.

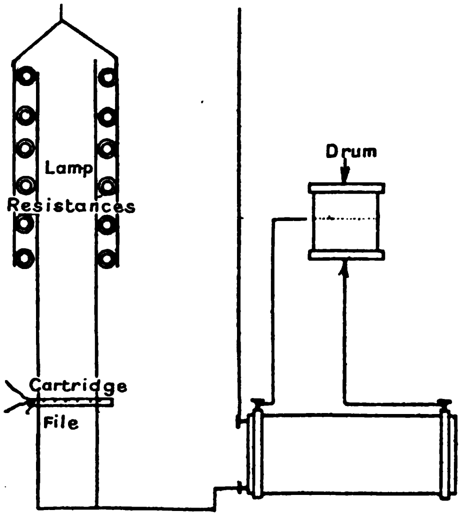
As the rate of detonation is admittedly dependent upon, or influenced by, the diameter of the cartridge, it may be assumed that it would also be perceptibly affected if the cartridges be contained in some resistive envelope. Such was Dr. Mettegang's argument, and his apparatus practically embodied it. During the last year or so, it has been used in testing a great number of explosives and has proved thoroughly trustworthy.

The principal items of this contrivance are an electric current, a sparking induction coil, and a rotary recording drum. The current may be taken from any electric lighting circuit having a terminal pressure of from about 110 to 220 volts. The current is divided and shunted through two equal lamp-resistances and then jointly connected to the one pole of the primary induction-coil through which the current passes back to the return conductor (see Fig. 11). The primary coil thus receives the current through 12 lamps. One pole of the secondary coil is connected to the bearing of a soot-blackened rotating vertical drum, the other pole carrying a fine platinum point placed about ¼ millimetre from the drum surface. Any change in the tension of the current passing through the primary coil sets up an induced current in the secondary coil and causes sparking from the platinum point; to ensure a high potential no iron core is used in the primary. If the two connecting wires passing from the lamp resistances to the inductor are made to intersect the two ends of the cartridge-file to be tested, the time interval is marked on the recording drum in the form of tiny specks.

In order to obtain legible records on the drum its speed of rotation must be properly adjusted to the rate of detonation and the length of the cartridge-file. A diameter of 30 millimetres and a length of from 3 to 4 metres have been found suitable dimensions for the latter. The cartridges are enclosed in an iron pipe.

The readings obtained by the old method differ but slightly from those by the new, whilst the latter possesses distinct advantages over its predecessor. It is less costly, its manipulation simpler, and, as much smaller charges are sufficient (about $\frac{1}{10}$), the experiments can be carried out anywhere. Unlike other electro-chronographs, the action of the Mettegang Recorder is *purely electrical*, whereby errors of observation are eliminated.

FIG. 11



The highest rate of detonation recorded is about 8000 metres per second. Four metres of cartridges would therefore detonate in $\frac{1}{2000}$th part of a second. Hence with a rotary speed of 25 metres per second, the markings registered on the drum would be 12½ millimetres or ½ inch apart.

The upper and lower periphery of the drum is finely tooth-geared to a regulating screw by which, with the help of a filar eyepiece, it is possible to read the intervals marked on the drum $\frac{1}{100}$th part of a millimetre ($\frac{4}{10000}$ inch) apart.

Uniform results can only be obtained by adhering to a certain, not too small, cartridge-diameter, and by filling the cartridges into a wrought-iron pipe so as to imitate the conditions of a genuine borehole. In so doing, it should be borne in mind that for every explosive there is a certain density which is most favourable for its detonation, and that the different explosives should therefore be filled into the charging-pipe more or less firmly or loosely, as the case may be, in order to give each its fair chance.

If the pipes be buried 1½ metres deep in sand the report of the detonation is deadened and no iron fragments fly; the trials can therefore be conducted within a few hundred yards of works or dwelling-houses. If it is desired to work with unenclosed cartridges, an arched cardboard roof is placed over the file at the bottom of the ditch, which is then filled up with sand.

It might perhaps be objected that for every decrease of potential or interruption of current in the primary coil a certain time must elapse before the tension in the secondary coil is sufficiently raised to cause sparking; but such possible varying retardation may be reduced to a negligible quantity, as the tension of the alternate sparks may be equalised by means of the lamp resistances.

The sparking does not mark the drum singly, but, owing to electric oscillation, produces a number of dots.

Example of test:

Gelatine Dynamite
Length of cartridge-file = 3.78 metres
Peripheral rotation of drum = 23.46 metres per second
Indicated space between successive series of dots = 12.79 mm.
Hence 12.79 mm. = 0.546 millisecond, and
3.78 metres in 0.546 millisecond correspond to 6915 metres per second.

CHAPTER VI

LENGTH AND DURATION OF FLAME

On detonation the heat of decomposition causes the various explosives to develop flame of different extent and duration. The range of the flame depends on the quantity of the explosive detonated. Other explosives within striking reach of that flame can be detonated thereby, and gas-mixtures ignited if contact be long enough.

Several attempts have been made to determine the length of flame by placing ignitable substances in varying proximity, but it is by means of photography that numerical results have been ultimately obtained. The plant (designed by Dr. Mettegang for the purpose) was as follows:

A steel mortar of the kind used in trial galleries was placed in an upright position with a graduated scale behind it. The explosives to be tested were fired from this mortar in the usual manner. The shots were photographed at night, a quartz camera lens being employed to focus the ultraviolet rays (attending extreme heat) upon a rotary drum covered with a sensitised film. A screen with a stenopaic slit was inserted between lens and drum close to the latter. With the drum at rest the height of the photographic image represents the length of the flame, the breadth of the image being that of the aperture in the screen. When the drum is in rapid motion the image is laterally blurred. The lateral extension of the image, when applied to the rotary speed of the drum, represents the duration of flame in milliseconds.

Specimens of flame images are shown in Figs. 12 to 15.

The limit values for the *length of flame* of the safest and the least safe of the explosives tested, *viz.*, Kohlencarbonit and Blasting Gelatine, lie between 0.40 and 2.24 metres, or in the ratio of 1 : 5.6. The limit-values for the *duration of flame* of these two extreme types are $\frac{0.28}{1000}$ths and $\frac{10}{1000}$ths of a second, or in the ratio, therefore, of 1 : 36.

CHAPTER VII

"AFTERFLAME RATIO"

A CONSIDERATION of Table III., which shows the explosives arranged according to their respective safety, their rate and temperature of detonation, and length and duration of flame, leads to conclusions going somewhat beyond those based on results previously obtained, viz., by comparing the rate of detonation (taken as unity) with the duration of flame, as shown in column 9. One of the safest explosives, Kohlencarbonit, thus shows the proportion 1 : 8.7, whilst blasting gelatine, showing a proportion of 1 : 883, would appear to be 100 times less safe than the former.

This striking difference is doubtless due to the fact that with less safe explosives the detonation-time is short and the duration of the flame long, whereas with the safer explosives the relation is reversed.

The relation between detonation-time and duration of flame may perhaps not inaptly be called "afterflame ratio," the expression being convenient for defining different degrees of safety; a large afterflame implying an unsafe, and a short afterflame a safe, explosive.

The following figures show the comparative ratios of the safest and least safe explosives as to rate of detonanation, length and duration of flame, afterflame ratio, and temperature :

THE SAFEST EXPLOSIVES COMPARED WITH THE LEAST SAFE

Detonation Time	Length of Flame	Duration of Flame	Afterflame Ratio	Temperature
1 : 4	1 : 5.6	1 : 36	1 : 100	1 : 2

The afterflame has thus the greatest influence upon the ignition of firedamp, but the length of the flame and the temperature are also of importance.

The flame of all explosives outlasts the time of detonation, but that of the "safe" explosives does so in a much less degree than in the contrary case. The range of afterflame, therefore, appears to be the determining factor in the ignition of firedamp, although there is also a certain correlation between the afterflame and the pressure. For the quicker the decomposition takes place and the longer the decomposition-products retain their temperature, the greater will be the pressure, but also the danger of ignition. On the other hand, the slower the decomposition, the lower the temperature of explosion and the quicker the condensation of the gases—the smaller is the pressure of the explosives and the greater is their safety in the presence of firedamp.

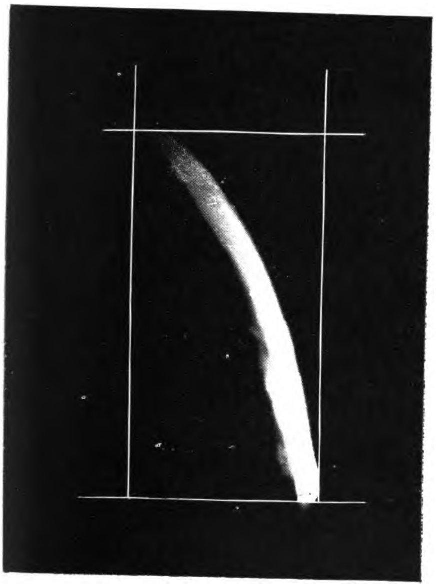
That the more or less speedy condensation of the gases depends on their composition, temperature, and, also, their mutual interactions, is self-evident. Thus, the safety of the ammonium nitrate explosives seems to be due to the amount of quickly condensing steam contained at a relatively low temperature in the resulting gases; the phenomena observed with other explosives do not permit of such easy explanation.

The application of spectrum analysis in conjunction with flash-light photography may, perhaps, give such

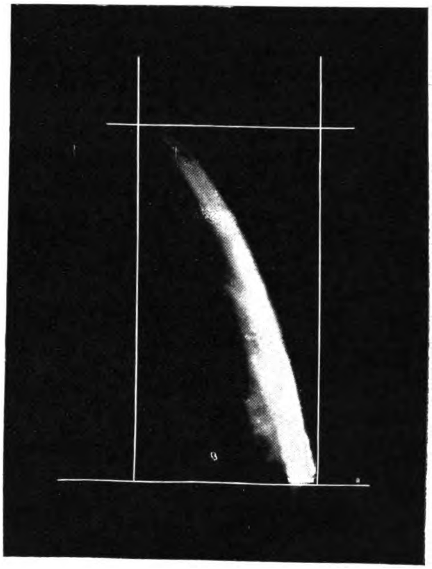
FLAME PHOTOGRAPHS

FIG. 12

(Speed of drum = 18.45 metres per second)



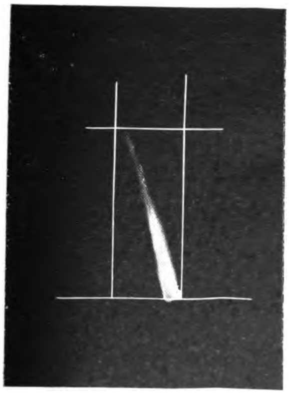
100 grammes Gelatine Dynamite
Duration of flame = 1.22 millisecond



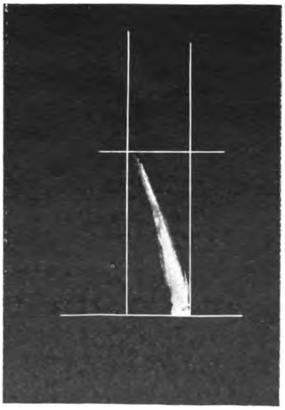
100 grammes Gelatine Dynamite
Duration of flame = 1.25 millisecond

FIG. 13

(Speed of drum = 18.45 metres per second)



100 grammes Ammoncarbonit
Duration of flame = .33 millisecond



100 grammes Carbonite
Duration of flame = .34 millisecond

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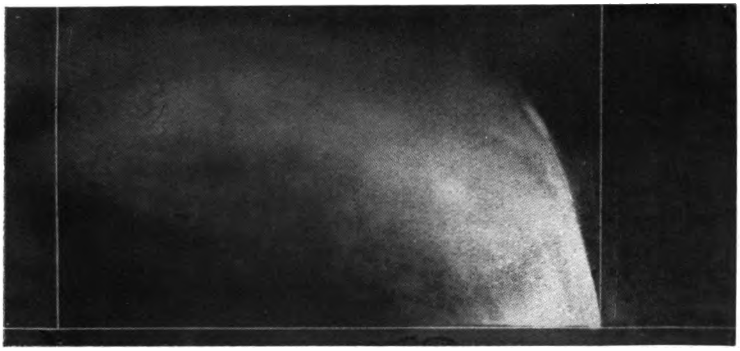
FLAME PHOTOGRAPHS

FIG. 14

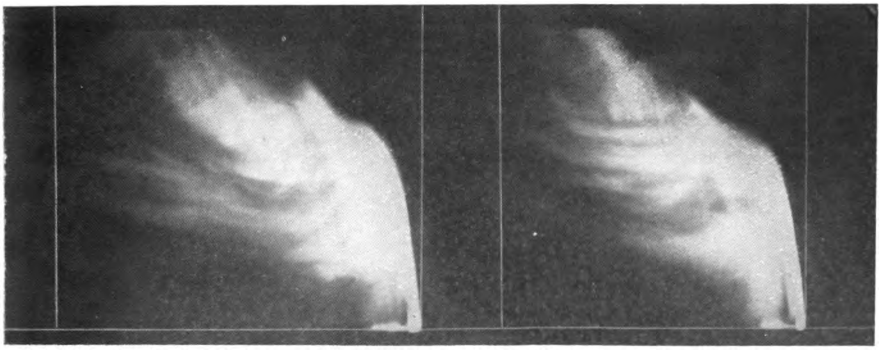
(Speed of drum = 18.22 metres per second)



100 grammes Dynamite I.
Duration of flame = 7.66 milliseconds

FIG. 15

(Speed of drum = 18.22 metres per second)



100 grammes Blasting Gelatine
Duration of flame = 11.15 milliseconds

100 grammes Blasting Gelatine
Duration of flame = 9.33 milliseconds

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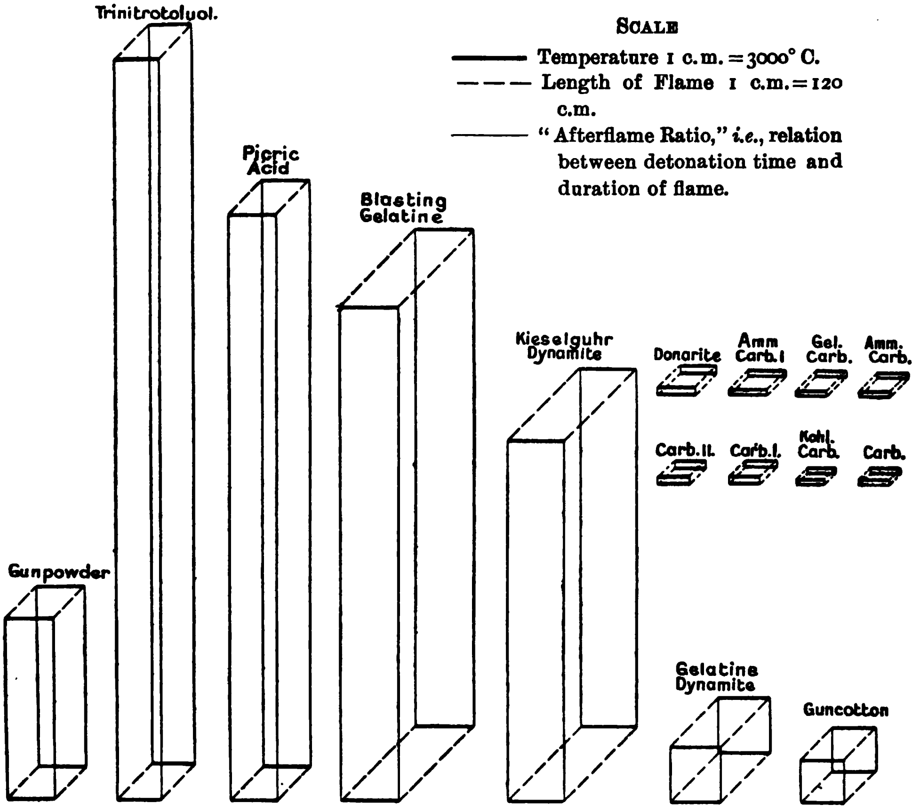
explanation, and the former branch of science may possibly provide a reliable experimental basis for measuring the temperature of detonation. Investigation in this direction is still progressing, and so far results have completely accorded with the experience gained from laboratory experiments upon inflammable gas-mixtures.

FIG. 16



SCALE

——— Temperature 1 c.m. = 3000° C.

– – – Length of Flame 1 c.m. = 120 c.m.

——— “Afterflame Ratio,” *i.e.*, relation between detonation time and duration of flame.

It is well known that an inflammable gas-mixture can be ignited by any incandescent substance of or exceeding the temperature of ignition provided that the surface of the substance be large enough and the contact last sufficiently long. With regard to the ignition of fire-damp we have to take into account :—temperature, length of flame, and especially duration of flame; the rate of detonation also plays a part, inasmuch as when very high, it may outpace the receding gas-and-air mixture in the gallery. The temperature of ignition of firedamp is known to lie between 600° and 700°C. (1112° and 1292° Fahr.), and is, therefore, considerably below any of the tabulated temperatures of detonation.

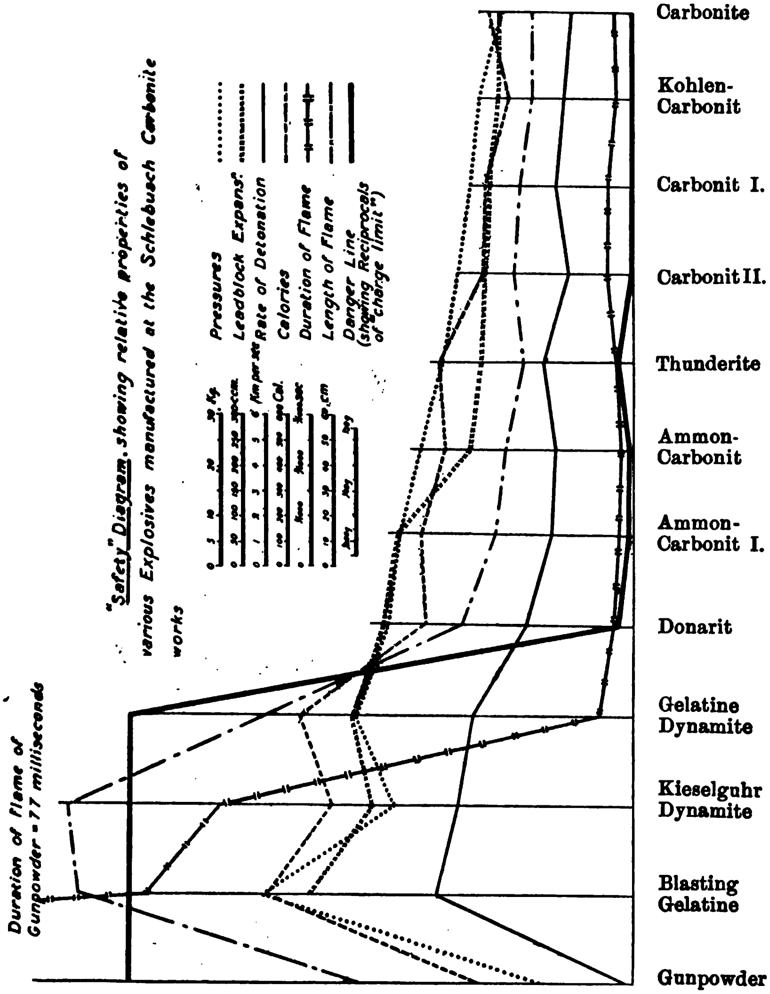
The diagram (Fig. 17) showing the factors which play a prominent part in igniting fire-damp, as well as the comparative values shown in Fig. 16 regarding the temperature, length of flame, and burning ratio, of various explosives, hardly need further explanation. Particularly striking are the different afterflames given off by safe and unsafe explosives.

The diagram-readings show, moreover, that the varying properties of the various explosives differ considerably with the charges used, and that the danger begins as soon as certain rather low charge-limits have been exceeded.

Analogous characteristics are shown by the Kohlen-carbonit, the ammonium nitrate explosives, gelatine dynamite and gun-cotton; the unsafest group being the more brisant explosives and gunpowder. The limit which guarantees safety for mining purposes lies within the group of the ammonium nitrate explosives, whilst danger begins where the composition is incompatible with the utmost reduction of temperature, length of flame, and afterflame ratio.

From ocular observation of the afterflame it is easy to understand why each explosive should have its *charge limite.* **All explosives show afterflame, which increases in volume with the charge.** This is manifest not only from ocular observation of explosions, accidental or otherwise, of large quantities of explosives, but also from specific tests made for the purpose of ascertaining the maximum distance of transmission of explosion for

FIG. 17



different charges. When, for instance, the great explosion at Keeken on the Rhine occurred in 1895, involving 18,960 kilogrammes of dynamite and blasting gelatine, eye-witnesses stated that they noticed an enormous flame. A similar experience was recorded during the blowing-up of magazines on the Kunnersdorf shooting range in 1899, when dynamite charges of 500 and even 1500 kilogrammes were exploded, and enormous flames were witnessed and photographed.

CHAPTER VIII

TRANSMISSION OF EXPLOSION

If two cartridges of one and the same explosive are placed end to end on the ground and fired unconfined by a detonator inserted in one of them, the explosion of the first cartridge is transmitted to the other. If, however, a space is left between them and increased for every successive experiment, then it will be found that the range of transmission is not the same for all explosives but that, on the contrary, each possesses the faculty of transmission in a different degree. For example, it has been proved that while 10 kilogrammes of nitro-glycerine compound transmit the explosion to another charge of ½ kilogramme 4½ metres away, an equal charge of any of the ammonium nitrate explosives will only do so up to a distance of ½ metre.

During a series of experiments of transmission made towards the end of the nineties, the flame emitted by different charges of explosive was also measured. This was done by exploding charges of gelatine dynamite varying from 1 to 200 kilogrammes, surrounded by a number of secondary charges of from ½ to 2½ kilogrammes of dynamite fixed on poles placed in concentric circles so as to be immediately exposed to the effect of the central explosion. It was further proved that when both the initial and the secondary charges were placed underground, transmission of ignition only took place at very short distances, which leads to the conclusion that it is only the direct flame-effect which causes a transmission of the explosion to the second charge, and not the concussion, as was formerly believed. The expression "explosion by sympathy," which has often been used as a variant term for transmission, is therefore clearly a misnomer.

For gelatine dynamite the distances of transmission ascertained were as follows:

1 kilogramme	0.8 metres
5 "	1.45 "
10 "	1.80 "
25 "	2.25 "
50 "	2.50 "
100 "	2.75 "
200 "	5.25 "

At the accidental explosion at Keeken of nearly 9½ tons of dynamite and blasting gelatine, two lots of 150 kilogrammes each of dynamite were exploded by transmission at distances of 40 and 50 metres respectively, while a third lot 70 metres away remained intact.

This, no doubt, points to an increase of flame with the increase of charge, and also explains why there should be a *charge-limite* for the different explosives, seeing that of all the phenomena accompanying detonation the after-flame is the most critical element in regard to safety.

CHAPTER IX

CONCLUSIONS

The tabulated results of the foregoing investigations have been arranged so as to place the various explosives in a series according to their safety. The columns referring to force combine, as might be expected, with those of safety in fairly reciprocal relation, and thus show an inverse progression. (This does not, of course, refer to gunpowder.)

The calorific values exceed those for pressure in the case of the more powerful explosives; with the less powerful the reverse is the case. Indeed, had the results been parallel, they would have pointed to the conclusion that the gases produced expand in direct proportion to the heat generated, a result contrary to experiment.

The rates of detonation follow the pressure-values with fair uniformity.

The strength, or "mining power" of explosives, is proved to be directly proportional to the quantity of heat and rate of detonation; how far it is influenced by the various quantities of gaseous products and their chemical composition *at the moment of detonation,* still remains an open question.

As to danger in the presence of firedamp, gunpowder, blasting gelatine, Kieselguhr dynamite and gelatine dynamite must be considered very unsafe. The nitrate of ammonia compounds (except Donarit, which is only intended for use in potassium salt mines and in quarries) are all sufficiently, the Carbonite varieties pre-eminently, safe. To the various phenomena affecting safety must be added the length and duration of flame. In the case of gunpowder, these latter are alone decisive, other elements of danger being absent. The dynamites, on the other hand, exhibit all the undesirable factors.

Ammonium nitrate compounds give a longer flame and higher temperature and pressure than the Carbonites, hence the greater safety of the latter. There is reason to believe, besides, that the temperature of the fumes at the moment of explosion also carries weight. Taken collectively, all the values for the Carbonites keep within moderate limits, and it is, perhaps, to this circumstance that their great safety is attributable.

In general, safety explosives should show a minimum rate of detonation and a minimum of length and duration of flame at a given pressure; none of these should exceed certain limits, as the detrimental effect of one of them cannot be counterbalanced by the others, however favourable. Thus it is the long contact between flame and gas-mixture which is fatal to gunpowder in spite of its low calorific value. To " detonate " gunpowder even with a detonator is impossible, accelerated combustion, at the best, taking place. The heated gases remain too long in contact with the inflammable gas-mixture, and thus, even at low temperatures, ignition is unavoidable.

Explosives containing high percentages of nitroglycerine detonate very quickly—so quickly that the gas-mixture in the gallery cannot recede in time and is struck by the long flame; although this contact is instantaneous, ignition takes place in consequence of the high temperature.

As gelatine dynamite gives a considerably shorter flame-time than blasting gelatine and Kieselguhr dynamite, without, at the same time, being safer, it may be assumed that it is the higher amount of heat and rate of detonation of the former which cause ignition.

As already shown, the greatest safety is only attainable when all the observed values are within certain bounds. That nevertheless, after a certain *charge-limite* has been exceeded, ignitions do occur in the testing-galleries even with the safest explosives, is quite in keeping with the transmission tests, according to which the flame length increases in proportion to the charge.

Charges of more than 1 kilogramme cannot well be used for experimental work without risk of damaging the apparatus; heavier charges, however, are but rarely required for ordinary mining work.

CHAPTER X

EFFICIENCY

THE exertion of chemical activity in a borehole on explosion of a blasting charge is obviously beyond the scope of immediate observation, as the conversion of explosives into gases is too rapid for scrutiny. In order to get an insight into the probable happenings attending an explosion one is therefore compelled to picture the sequence of events with a view towards applying such means of observation as may be applicable at certain points or stages.

In blasting operations a properly prepared shot-hole is charged with cartridges of a suitable diameter, which are inserted one by one and gently pressed home so as to ensure perfect contact with the walls of the borehole. The last cartridge is primed with a detonator and fuse and pushed in until it touches the top cartridge, when the remainder of the hole is firmly stemmed with good tamping material. To obtain the maximum effect no empty space must be left in the shot-hole, and the stemming should be as firm as possible to ensure the maximum resistance against the pressure of the gases of explosion.

On firing the shot, the flame of the powder fuse—or, in the case of electric fuses, the current—ignites and explodes the fulminate in the detonator. The intensely hot products of decomposition of the fulminate flash into the first cartridge, which is detonated and, in its turn, causes the explosion of the next, and so on from cartridge to cartridge, until the last one is reached. The whole of the charge is thus converted into new combinations, either gaseous, solid or liquid, as the case may be, which immediately strive to occupy an increased space due to their gaseous transformation and are under further potential expansion derived from the heat produced by the explosion. If the shot does its work, the resulting gases shatter the borehole, and escape through the broken mass; the mechanical work thus expended and the subsequent contact with the surrounding air cause the gases to cool and ultimately to diffuse.

The question is by what means can these phenomena be gauged ?

Between the detonation of the first and last cartridge there is a lapse of time which can be measured with sufficient exactness by means of apparatus already described, and it is this "rate of detonation" which enables us to gauge the dynamic energy of the products of explosion. For it is the velocity at which the superheated gases, during and after formation, acquire a displacement of frequently over a thousand times the volume originally occupied by the explosive, and at which they are projected against the resisting walls of the shot-hole with disintegrating, scorching, melting, and even vaporising effects. Both gases and vapours must necessarily fully participate in this kinetic energy generated by the detonation, whilst the more inert and solid products of decomposition, though doubtless acting as projectile bodies, are not impelled with the same force owing to their lack of expansion. Nevertheless, in computing the total converted energy of a given explosive, the whole of its constituents must be considered, as it is only reasonable to assume that such products as may be solid at ordinary temperatures will, in the majority of cases, be molten or even vaporised at the actual moment of explosion.

The energy imparted to the products of decomposition by the detonation may be expressed thus:

$$\frac{M v^2}{2},$$

M representing the mass of the decomposition-products and v the rate of detonation.

The calculated value of this kinetic energy represents the "percussive force" of the explosive.*

But a further factor must be taken into account, viz., the pressure developed by expansion of the superheated gases. As shown in the preceding chapters, the calculated temperatures of explosion were arrived at on the basis of the total heat developed by given quantities of the different explosives, the specific heat-values employed being those of Messrs. Mallard and Le Chatelier, and the products of decomposition being determined by analysis. Adopting the temperatures so calculated, and assuming that Gay-Lussac's law for the expansion of gases

$$V = V_0 \left(1 + \frac{t}{273}\right)$$

holds good at such temperatures, the pressure exerted by the heated gases and vapours may be deduced. In

---

* This depends upon the assumption that the observed rate of detonation is identical with the velocity of the molecular projection. A very interesting chapter on the ballistic theory of explosives, and one well worthy of re-perusal, appeared in 1891, in a contribution by Mr. Stephen H. Emmens to the U.S. Naval Institute, entitled "Explosives and Ordnance Material" (vol. xvii. No. 3), in which the imperative necessity for studying molecular ballistics apart from concomitant pressures is insisted upon. This author, however, does not consider the rate of detonation an essential, and his mass and velocity factors, therefore, differ materially from those suggested in these pages.—Tr.

Table IV. will be found diagrams of comparative percussion- and pressure-values with the data involved in their calculation. Whilst the percussive force is a *dynamic* action, expressible in kilogramme metre-seconds, the pressure, due solely to the thermo-expansion of highly compressed gases and vapours, must be considered as *static* energy, and is therefore expressed in kilogrammes per square centimetre.

As regards the simultaneity of the two kinds of energy there can be no doubt that both percussion and pressure are generated as soon as the decomposition of the explosive begins, but beyond that there is, strictly speaking, no implied coincidence in time, seeing that the maximum pressure cannot be reached before the decomposition of the whole of the charge, *i.e.*, until after the percussive force has been fully developed. Whether any general correlation exists between the equivalents of the two forms of energy can only be conjectured, but it seems more than doubtful. All that is definitely known is that any increase of the percussive force also involves an initial increase of the potential pressure.

It would be interesting if, by means of suitable apparatus, the percussive force and the pressure of explosives detonating in their own volume could be determined by direct measurement; but, unfortunately, the violence of the former and the intensity of the latter are such as to render the direct measurement of ordinary (mining charge) explosions a task exceedingly difficult, if not impossible, of realisation. We can, however, check the correctness of the calculated tables indirectly by comparing these with the results obtained in practice.

If, for example, gunpowder be compared with brisant explosives, experience shows the former to be greatly lacking in percussive force. So much so, in fact, that if a powder charge be fired from a bore in hard tough rock it is "blown out," as from a gunbarrel, without shattering or even perceptibly affecting the borehole. It is this very deficiency in percussive force which renders gunpowder a suitable propellant for use in guns; high explosives with violent percussive force would burst them.

That the brisancy of high explosives varies in degree, according to the relative rate of detonation, is confirmed by experience of the miner, who finds that the harder and tougher the rock the "stronger" must be the explosive. A suitable agent to employ under such conditions is blasting gelatine; this can be used in cartridges of small diameter, (diminishing boring costs,) due to the fact that, as shown in the foregoing, it requires a smaller space in which to develop a high rate of detonation than do explosives detonating at a slower rate. Again, explosives of the latter class (more particularly those of the ammonium nitrate type, the pressure of which never reaches that developed by high-percentage nitro-glycerine compounds) are found advantageous mainly where the rock surrounding the borehole is easily shattered by the heat of explosion, quickly crushed by the percussive force, and readily disintegrated by the gas-pressure. Here a more violent explosive would obviously be of little use, for whilst the percussive force would instantly create an increased space, neutralising the advantage of a small charging-density, the final gas-pressure would also be lowered by the quicker condensation of the products of decomposition on contact with the larger surface area produced. Miners speak of such a shot as "having killed itself," perhaps an appropriate description of what actually takes place.

If the object of blasting were merely to crush or shatter, then, no doubt, violent explosives would serve best. But as practical mining rather involves the shifting and "getting" of masses, it stands to reason that this will be accomplished more easily and economically by using a less violent agent, *i.e.*, one with a lifting or heaving action. In soft ground again, it is pressure which must mainly accomplish the work, and as highly percussive explosives would interfere with this action, they are unsuitable.

This principle also holds good in military mining, where old fashioned gunpowder, devoid of percussive force which "kills itself" in soft ground, still maintains preference over numerous modern and more powerful rivals.

As regards the absolute figures given in the table and their practical value, it is essential to bear in mind that they have been calculated for charges under constant volume. But such a permanently unyielding envelopment as is here assumed does not exist, even the hardest material yielding to the force of an agent exploding, as nearly as possible, in its own volume; some change of volume instantly occurs as soon as decomposition is initiated. The tabulated values for the theoretical maxima of pressure are therefore subject to certain reductions which increase in proportion as these values approach the absolute. In reality, therefore, the percussive force and pressure do not fluctuate to nearly the extent shown in the diagrams but rather come down to the level indicated by empirical experience.

With this reservation the figures given in the table cannot be said to be inconsistent with general practice; on the contrary, if due allowance be made for the fact that the maximum (theoretical) potential of an explosive can never be developed in practice, they tally well with our practical knowledge of explosive reactions.

It would appear that by resolving an explosive effect into dynamic and static components—a view, as we have seen, strongly supported by the evidence available—a more rational classification of explosives is offered than by formulating both together. Any formula expressing such joint action would necessitate the introduction of a factor representing the surrounding material, for, as already pointed out, the maxima of percussive force and of the pressure exerted by an explosive vary inversely with the resistivity of the ground. As the former is capable of out-travelling the pressure where the disruption is instantaneous, but little would in that case remain for the latter to accomplish. It follows that such considerations must inhibit the inclusion of both effects in one formula.

Again, it is conceivable why it should have proved impossible to devise a standard power-gauge for testing brisant explosives, as no material can be found in which the percussive force and the pressure meet with the same resistance at the same time. We know how misleading the results of the Trauzl test are when compared with those obtained under working conditions. High percussive force and temperature give excessive lead-block expansions, whilst in practical blasting it is generally the less violent type of explosives which works out most economically. Gunpowder, which hardly shows any percussive action, gives no appreciable lead-block expansion for reasons already explained. On the other hand, it is found that gauges based on static methods, and thus better adapted for measuring the pressure of gunpowder, are useless for testing high explosives.

By adopting the methods now introduced, *i.e.*, distinguishing between, and separately considering, dynamic and static actions, the necessity for taking the material to be blasted into account is obviated, and the problem of classifying explosives according to their practical value receives a ready solution; thus, with the data now available it should henceforth be an easy matter, both for

FIG. 18

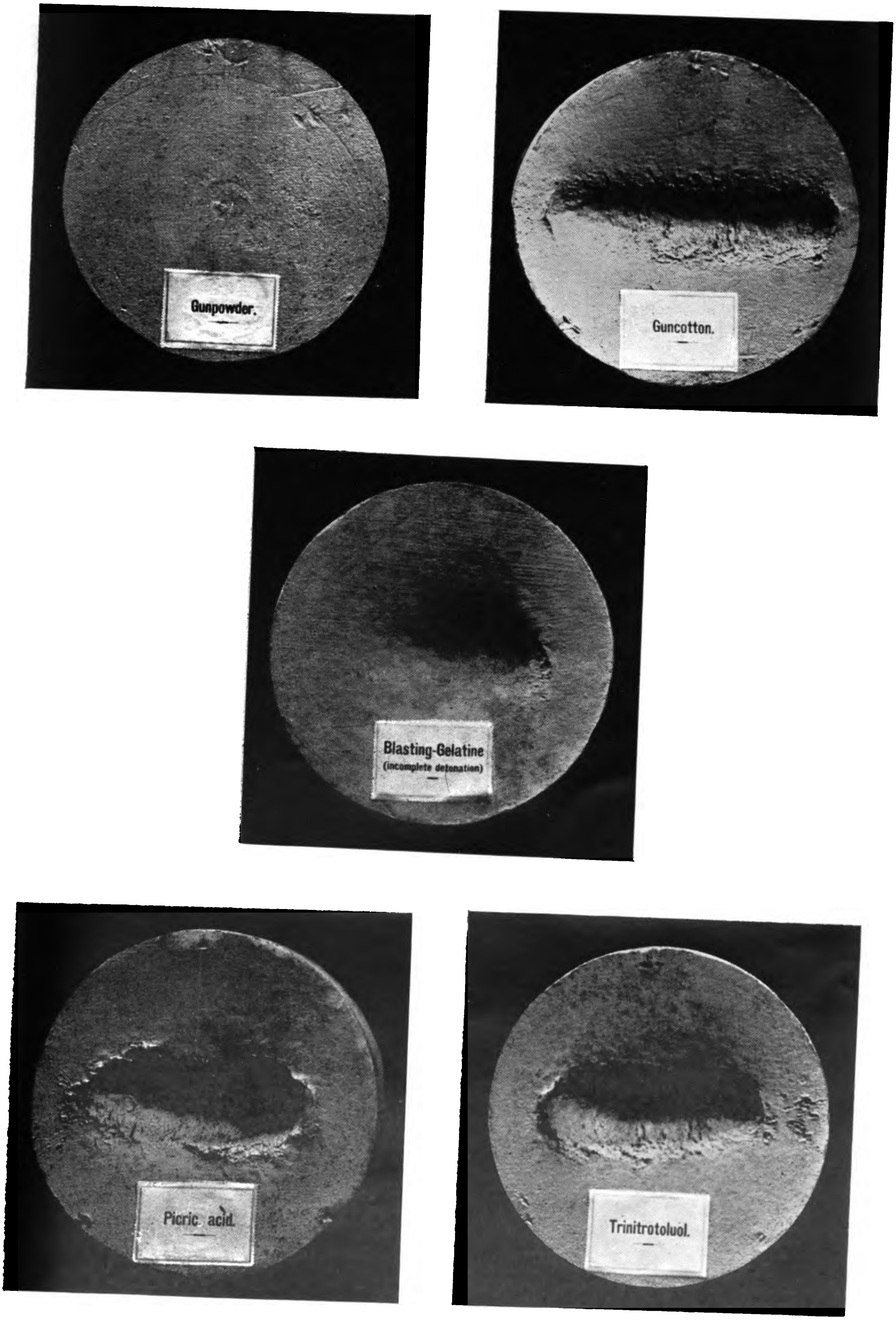
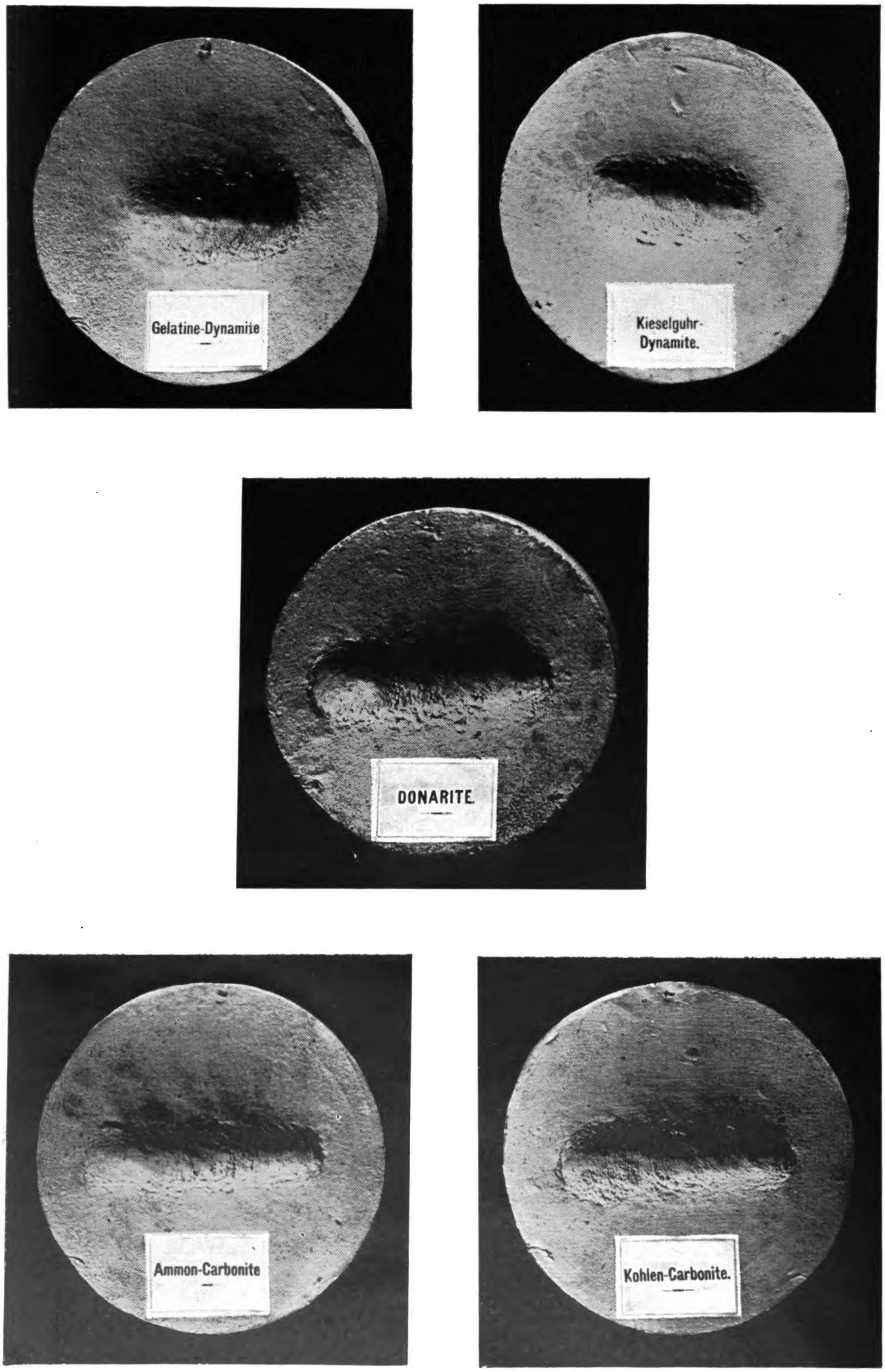

Gunpowder.
Guncotton.
Blasting-Gelatine
(incomplete detonation)
Picric. acid.
Trinitrotoluol.

FIG. 19


Gelatine-Dynamite
Kieselguhr-Dynamite.
DONARITE.
Ammon-Carbonite
Kohlen-Carbonite.

the mining engineer and for the artillerist, to make a suitable selection.

The part played by the other factors given in the tables of percussive force and pressure require a few words.

The formula for kinetic energy embraces the mass of decomposition products set in motion, and the square of the rate of detonation. It is to the latter, therefore, that the percussive force is mainly due. This force is developed by confined and unconfined charges alike, and can thus be demonstrated in a plastic manner, for example, by firing cartridges placed on lead-discs. In the accompanying photographs (Figs. 18, 19) a number of shots so fired is shown. It will be noticed that explosives manifestly possessing the highest percussive force leave the deepest depressions in the plates. In the case of blasting gelatine, which is known to detonate imperfectly when unconfined, the depression is somewhat irregular; otherwise the results are fairly in keeping with the theoretical deductions.

The formula expressing the gas-pressure comprises the volume in which the detonation takes place, the gases and vapours resulting within such volume, and the temperature. The pressure exerted by a given explosive in its own volume therefore depends upon the quantity of gaseous products, the charging density, and the temperature of explosion. For purpose of calculation it is further assumed that the enclosing walls are absolutely non-yielding and that Gay-Lussac's law applies to the pressures and temperatures which occur in practice.

Whether this law still holds good for pressures of 18,000 kilogrammes per square centimetre and temperatures exceeding 3000°C., is not known. If this is not the case, the calculated absolute values would not be perfectly correct, but they still form a useful guide for comparing the practical values of explosives. The problem can only be finally decided when means are found to measure such high pressures directly.

Seeing the important progress that has been made in measuring abnormal energies, however, it is perhaps not too much to hope that apparatus may yet be found which will register the absolute pressures generated by explosives. Meanwhile it is still possible to measure the pressure with reduced charging densities by means of Bichel's pressure-gauge previously described. It has been thought useful to compare the pressures calculated from calorimetric indications and according to Gay-Lussac's formula on the basis of a charging volume of fifteen litres, with those registered experimentally, and the two series of results have been added in Table IV. column 13. Considering the wide dissimilarity of the two methods it is satisfactory to note the concordant results obtained, and it therefore appears that for these charging densities both methods rest on correct foundations. Whether the calculation method is equally applicable to higher charging densities and constant volumes, is at present impossible to say with certainty. Judging, however, from empirical observation, there appears to be but little doubt that such is the case.

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BLE I.—1902

5 Number of calories developed by 1 kilogr. of explosive	6 Pressure develop. by 100 grms. in 15 litre chamber after elimination of surface influence	7 By lead block expansion dia. and height of block = 20 cm. charge = 10 grammes	8 Rate of detonation	9 Duration of flame from 100 grm. of explosive	10 Length of flame from 100 grm.	11 Ignition occurred in 7% firedamp and coaldust mixture with	12 Reciprocals of values in preceding column	13 Cartridge of 1¼" diam. transmitted explosion at a distance of	
	Kilogr.	Cub. cm.	Metres/sec.	Millisec.	Millimetres	Grms.		Millimetres	
574	18·7	No result	2 to 300	77	110	5	0·2	Not measured	
1422	70·4	650	7700	9·72	224	5	0·2	Unconfined. Incomplete detonation	Nitro-glyc. Explosives
1170	48·2	520	6818	8·31	228	5	0·2	310	
1321	55·4	560	6210	1·23	150	5	0·2	250	
836	48·7	500	3930 confined 4137	0·40	69	130	0·0077	60	Ammon. Nitrate Explosives
850	46·8	470	1753 confined 3195	0·32	56	300	0·0033	60	
757	42·25	330	1649 confined 3094	0·28	51	500	0·002	50	
77	38·0	310	2137 confined 3654	0·33	43	150	0·0066	30	
2	34·7	300	2472	0·53	48	900	0·0011	190	Nitro-glyc. Explosive
1	32·4	290	3042	0·47	45	1000	0·001	190	
[illegible]	31·0	270	2700	0·31	41	1100	0·0009	150	
[illegible]	26·6	265	2443	0·33	40	over 1100	0·0009	200	

E II.—1902

idues, solid and liquid			Total amount of gases formed during detonation		1 Kilogramme Explosive yields on detonation					
Carbon dioxide		Permanent solid or molten substances during detn.			Gases				Solids or liquid substances	
Gas	Gas									
9	10	11	12	13	14	15	16	17	18	19
Grm.	Lit.	Grm.	Grm.	Lit.	Lit.	1 Litre weighs Grm.	Grm.	Per cent.	Grm.	Per cent.
19·56	10·49	140·64	165·36	118	386	1·402	540	54	460	46
0	0	0	102·0	86·78	851	1·175	1000	100	0	0
0	0	25·00	75·5	56·85	536	1·33	750	75	250	25
11·85	6·36	51·82	104·18	75·99	487·5	1·37	668	66·8	332	33·2
0	0	0	206	218·04	1023	0·946	1000	100	0	0
4·3	2·31	11·94	194·06	189·91	922	1·003	942	94·2	58	5·8
4·4	2·36	13·8	192·2	191·55	930	1·002	932·8	93·28	67·2	6·72
0	0	0	206	210·55	1021	0·979	1000	100	0	0
14·18	7·61	64·87	141·13	153·72	746·5	0·919	685	68·5	315	31·5
27·16	14·57	75·24	180·76	197·97	773·5	0·914	706	70·6	294	29·4
15·85	8·50	42·59	163·41	168·13	816·5	0·97	793·5	79·35	206·5	20·65
17·95	9·63	56·15	149·85	149·98	729	0·999	729	72·9	275	27·5

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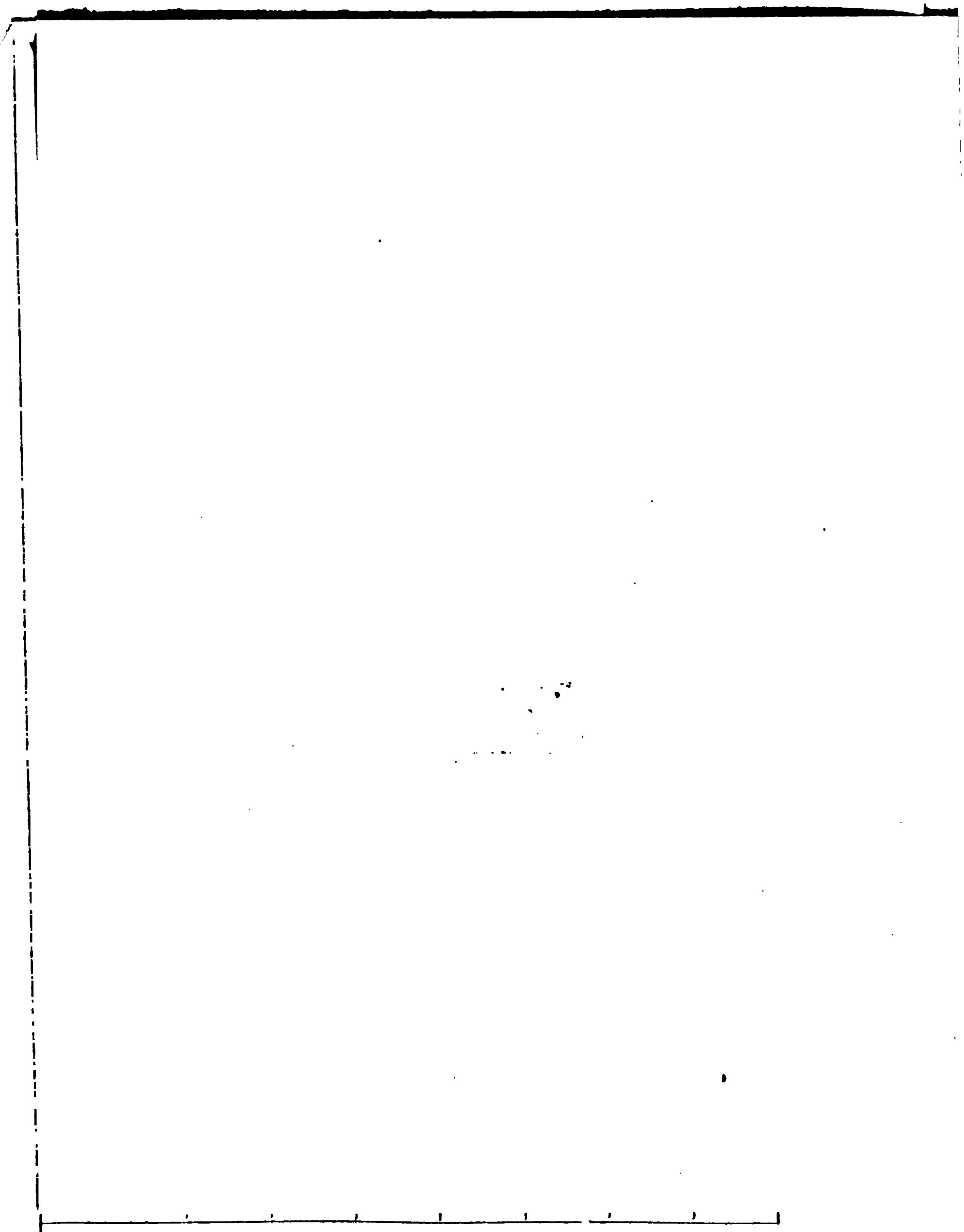

thods and are slightly at variance with previous results.

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